THERMOKARST EVOLUTION AND SEDIMENT TRANSPORT STUDY

IN THE CARIBOU-POKER CREEKS RESEARCH WATERSHED, ALASKA

By

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THERMOKARST EVOLUTION AND SEDIMENT TRANSPORT STUDY IN THE

CARIBOU-POKER CREEKS RESEARCH WATERSHED, ALASKA

A

Thesis

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Abstract

The role of sediment transport processes in the development and evolution of cryogenic features like thermokarsts have been overlooked by researchers. The current study is an attempt to better understand sediment transport and associated processes underlying the rapid growth of a thermokarst located in the Caribou-Poker Creeks Research Watershed. Within a short span of two warm summers, the study area has progressed from a hummocky terrain to a well incised channel configuration. Suspended sediment concentration and discharge analyses indicate high sediment flow following precipitation events, which play a major part in the sediment transport process. Mass sediment flows due to cryogenic piping were a result of interflow within the active layer. Fluvio-thermal erosion triggered block failures in the thermokarst. Topographical surveys spanning the two field seasons quantify the upstream erosion rate of more than 3.5 meters per year. Accelerated growth of the thermokarst has made the adjacent areas highly susceptible to secondary geomorphologic features.

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List of Symbols

Q	Flow rate of the fluid (l/s)
l/s	Liters per second
C	Sediment concentration (mg/g)
mg	Milligram

Acknowledgements

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Chapter 1

Introduction

Thermokarsts are depressions which develop subsequent to a disturbance of the surface thermal regime (French, 1996; Harry and French, 1983; Pewe, 1982; Czudek and Demek, 1970; Hopkins, 1949). Thermokarsts can occur in different environmental settings like forest clearings (Bosikov, 1998) and wooded areas (Burn and Smith, 1990) of the sub-arctic. Additionally, thermokarst features can develop below the surface of man made structures, gravel pads and buried pipelines. In interior Alaska, the number of instances of accelerated growth of thermokarst features has markedly increased in the past decade (Wu, 1981). Since the active layer is shallow in discontinuous permafrost regions, such sites are more vulnerable to permafrost degradation and terrain modification (Brown and Grave, 1979). Forest fire studies being conducted in the Seward Peninsula have seen major changes in the geomorphology of the thermokarst present in the vicinity of the burnt areas (Busey, R., personal communication). Thermokarst and the associated geomorphologic processes have interested scientists in the former USSR since the early part of the twentieth century and plenty of literature is available on studies conducted in Siberia (Czudek and Demek, 1970; Kachurin, 1962, among many others). In the United States, the studies initiated in 2004 at the Caribou-Poker Creeks Research Watershed (CPCRW) have reported rapid and catastrophic growth in a thermokarst located in the watershed (Toniolo et al., 2005; Kodial et al., 2005). Sediment erosion and deposition are integral components in the origin and development of thermokarst depressions and lakes

(Wallace, 1948); but, very limited research has been conducted on this major process and its impact on geo-cryologic structures.

1.1 Causes of thermokarst development

In a broad sense, the causes for the formation of a thermokarst can be grouped into regional or site specific causes and climate induced causes. The regional disturbances include forest fires (Burn, 1992), high rainfall events, and anthropogenic causes like road construction (Gallinger, 1991), pipelines (Thomas and Ferrell, 1983), and stripping of land for agricultural purposes. In some special cases anthropogenic disturbances can lead to favorable conditions for natural disturbances to take place (Walker et al., 1987). Lawson (1982) classified different kinds of human induced disturbances and the resulting modifications and studied their impacts on ground thermal regime. Disturbances lead to the active layer thickening every subsequent year after the initial perturbation to the thermal regime (French, 1974). With regard to climate change, the main factor is the increase in ground surface temperature which alters the thermal balance. Some additional climatic causes of thermokarst formation include thicker winter snow pack, or warmer summers (Murton, 2001).

The initiation of the accelerated growth of the thermokarst in CPCRW was probably generated by a major precipitation event that occurred in July 2003. Prior to this rain event the area was relatively stable and landscape modification due to soil erosion and ground ice degradation was insignificant. Figure 1 shows the discharge plot of the

Caribou Creek, located in CPCRW close to the thermokarst study site, indicating the peak flow that occurred in July 2003 (Bolton, 2003).

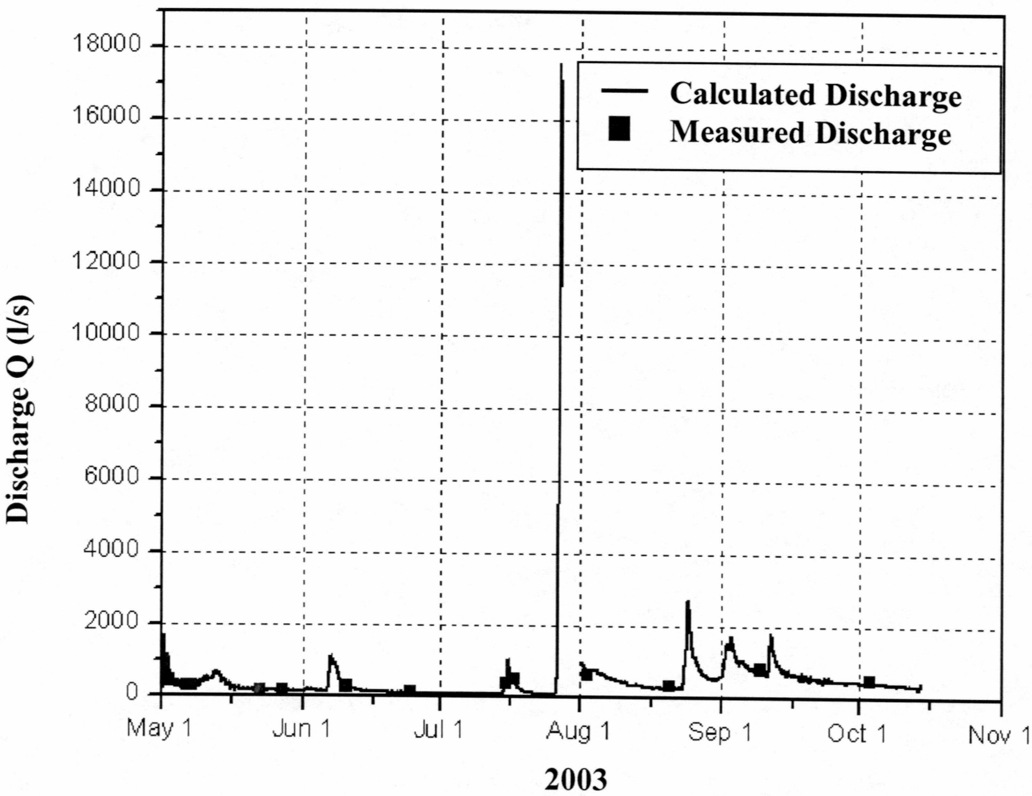


Figure 1. Discharge plot of the Caribou Creek located in CPCRW depicting the peak flow that occurred in July 2003 (Bolton, 2003).

1.2 Process of thermokarst formation

A well established process of thermokarst formation involves the following stages: subsidence or thawing, ponding, catastrophic or gradual drainage, surface subsidence and stabilization and associated surface and subsurface erosion (Hinzman et al., 2004; Yoshikawa and Hinzman, 2003). An earlier study conducted in CPCRW mentions that soil erosion, especially on slopes, occurs mostly during the summer (Wu, 1981). If the ground conditions are favorable for retaining the water present in the depression it could lead to the formation of a thaw lake or thermokarst lake (Kääb and Haeberli, 2001).

Thermokarst subsidence occurs when the energy balance at the ground surface is modified by any of the causes mentioned in the preceding section. This increases the heat flux to the subsurface layers thereby initiating ice wedge thaw and formation of terrain depressions. Once initiated the depressions may grow due to subsidence over successive summers. When conditions are favorable for water storage, ponding can be significant. Presence of subaerial formations such as pipes and sink holes may lead to drainage of the stagnant water depending on the groundwater static level. Gradually shore lines stabilize as the ground subsides. Erosion and sedimentation are the final steps in the thermokarst formation process. Figure 2 shows a schematic of thermokarst development process in a region of relatively thin permafrost (Hinzman et al., 2004).

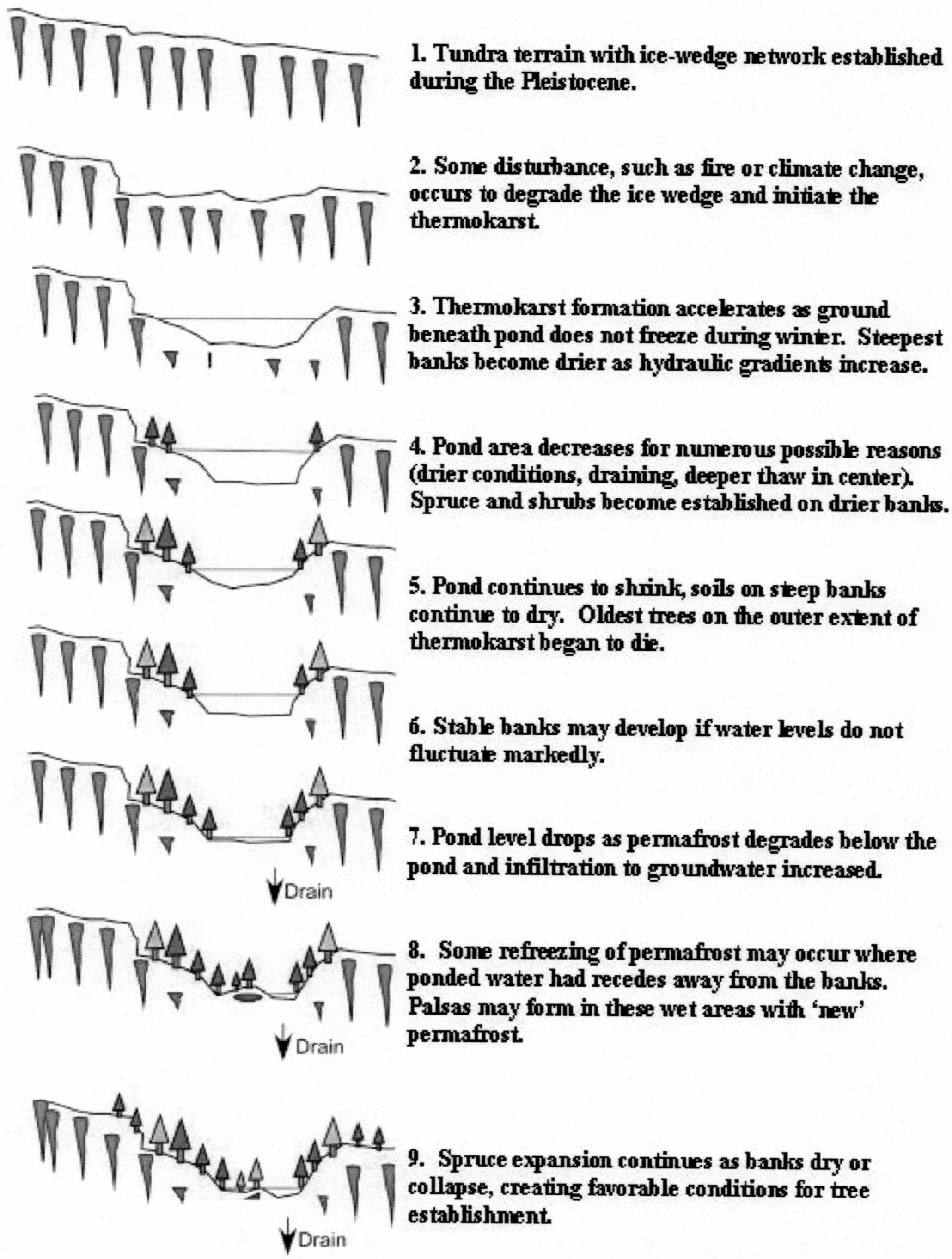


Figure 2. A conceptual schematic of the thermokarst development process in a region of relatively thin permafrost (Hinzman et al., 2004).

1.3 Active thermokarst features

There are some distinctive features that differentiate an active thermokarst from a mature stable thermokarst. These characteristics include but are not limited to the following three features, namely: 1) drunken trees; 2) slumping of banks; and 3) submergence of vegetation (Burn, 1992). Drunken trees are a common feature of the thermokarst located in the Caribou-Poker Creeks Research Watershed (CPCRW). These are randomly inclined spruce trees whose roots have been exposed by the degradation of the underlying permafrost (Kokelj and Burn, 2003). These trees will eventually die due to submergence. Associated active thermokarst features are the slumping and shearing of unstable banks followed by submergence of the top organic vegetation. The stabilization of slumps and bank erosion can be repeated every summer for a very long duration, 30-50 years (Brown and Grave, 1979). All the above mentioned features were observed during the two year study period, thereby justifying that the thermokarst in CPCRW is active. Figure 3 shows the photographs taken at two study sites, defined here as upstream and downstream sites, indicating the active thermokarst features in the flow direction.

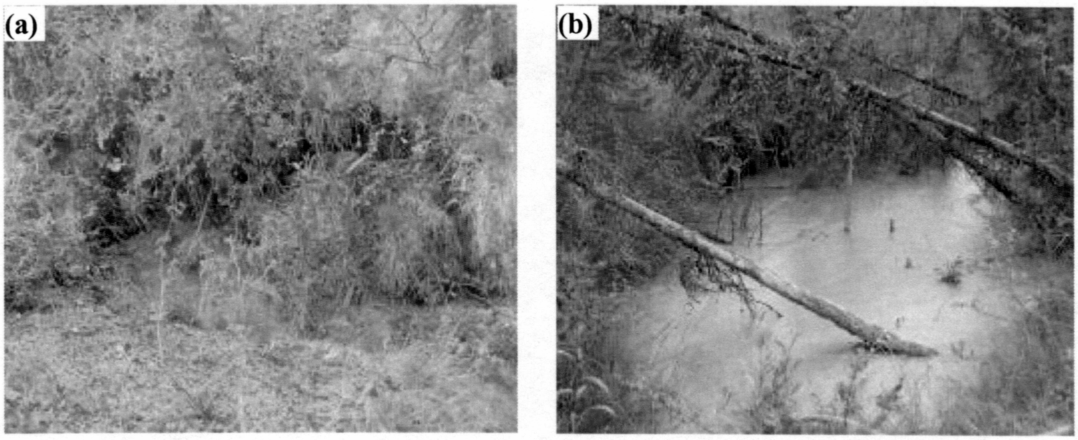


Figure 3. Active thermokarst features seen in the study area. (a) Slumping of the banks at the upstream study site; (b) Drunken trees at the downstream site. Flow direction in (a) is from left to right, and (b) from bottom to top.

1.4 Significance of thermokarsts in a changing climate scenario

The effects of climate warming in cold regions have received paramount attention by researchers in the circumpolar countries. The degradation of discontinuous permafrost in sub-arctic Alaska has been already reported (Osterkamp and Romanovsky, 1999). Coastal areas will be at higher risk from erosion and rise in sea levels if thawing of permafrost continues (Kane et al., 1991; Billings and Peterson, 1980). Increased development of thermokarsts in sub-arctic settings have been pointed out by Hinzman et al., 2004 and U.S. Arctic Research Commission Permafrost Task Force, 2003. A warming climate can lead to more permafrost degradation and subsequent formation of thermokarsts and thermokarst lakes in discontinuous permafrost environments (Kääb and Haeberli, 2001; Burn and Smith, 1990). Thermokarst depressions and lakes may be harbingers of climate warming by acting as surface expressions (Burn, 1992). Along with the thermokarst formations, a shift in the global climate can radically alter the ecosystem and associated processes (Jorgenson et al., 2001). Arctic and sub-arctic regions are at high risk if permafrost thaws due to climate change (Osterkamp et al., 2000) because total depletion of permafrost can lead to catastrophic surface modifications (Hinzman and Kane, 1992). Of special significance is the occurrence of thermokarst and related terrain disturbances at the southern boundary of discontinuous permafrost distribution because any change in climate patterns will first be observed at this permafrost/non-permafrost margin (Brown and Grave, 1979). It has also been reported that climatic warming may yield higher sediment loads in turn affecting the stability of hydraulic structures (Kane et al., 1991). The probability of recovery of disturbed terrain to its original stable configuration is very low as seen in three intensive study sites located in the National Petroleum Reserve-Alaska (Lawson, 1986). If measures are not enforced to control the degradation of perennially frozen sensitive sites in arctic and sub-arctic regions there may be drastic effects on the ecosystem and human activities.

1.5 Subsurface investigations and geo-cryogenic processes

In permafrost dominated environments like Alaska, the groundwater system simplifies to just three components namely: area of recharge, zone of transmission, and the area of discharge (Kane and Slaughter, 1973). Groundwater flow in the sub-arctic is affected by the presence of permafrost which acts like an impermeable boundary and prevents infiltration and recharge (Brandon, 1966). Furthermore, higher saturation of the active layer is favored in permafrost rich soils (Lewkowicz, 1983). Mackay (1983) conducted field and laboratory studies to show that in the summer, water can move downward into the active layer due to the combined effect of hydraulic and gravitational potentials. The subsurface water can be classified as subpermafrost, intrapermafrost, and suprapermafrost groundwater depending on its location with respect to the permafrost table (Dingman, 1976). Suprapermafrost groundwater is typically associated with continuous permafrost areas (Woo, 1986), but it can also occur in discontinuous permafrost areas. Suprapermafrost groundwater was evident in the thermokarst located in CPCRW from the subsurface investigations conducted in 2005. Hence subsurface investigations and the associated processes need to be better understood because the active layer is the first component that will be affected by permafrost degradation (Hinzman et al., 1997).

Chapter 2

Objectives

Several studies have been conducted on the thermal and hydrological aspects of thermokarsts and thermokarst ponds in arctic watersheds (Yoshikawa and Hinzman, 2003; Fraver, 2003; Burn and Smith, 1988; Kane and Hinzman, 1988; Lewkowicz and French, 1982; Dingman, 1976; Dingman, 1970). However, the role of sediment transport processes in the thermokarst development has been neglected. Previous studies have reported the type of sedimentary structures associated with thermokarst and thaw lakes (Murton, 2001; Hopkins and Kidd, 1988; Hopkins, 1949). But these investigations lacked a detailed insight into the sediment transport processes associated with permafrost degradation and surface subsidence in an anthropogenically and naturally disturbed milieu. The principal aim of this research was to assess the role of sediment transport and associated geomorphologic processes in the rapid evolution of the thermokarst.

2.1 Role of sediment transport in the evolution of the thermokarst

When permafrost degrades, the ice rich soil becomes highly susceptible to erosion and transport. Erosion can be initiated and accelerated by a number of causes such as flowing water, bank failure, precipitation and temperature rise in summer. The eroded material can be transported and deposited at a significant distance from its origin, thereby altering the topography of the area and inducing further modifications in the undisturbed sites. Hence, it can be hypothesized that sediment transport is an important mechanism for the evolution of an active thermokarst.

Objective: In order to test the hypothesis, suspended sediment concentrations were calculated over a period of two summers. The amount of suspended sediment being transported and deposited during different periods of the summer was investigated and the influence of flowing water on the suspended sediment concentration was analyzed. In conjunction with this, topographical surveys were also carried out to track the morphologic change and study the annual rate of thermokarst evolution.

2.2 Impact of cryogenic processes on terrain geomorphology

Permafrost degradation can be affected by a wide variety of processes. In many instances these processes can be localized depending on the terrain conditions like soil type, slope and vegetation. Several unique geomorphologic processes were observed at the thermokarst site since the initiation of its evolution. Significant among these were fluvio-thermal erosion, cryogenic piping, intra-active layer flow and associated sediment deposition in preexisting depressions. All these processes had a major impact on the sediment erosion, sediment transport, and the development of new landscape features.

Objective: In order to monitor the effects of cryogenic processes on the local topography detailed field observations were conducted when the underlying ground-ice was exposed. Temperature profiles along the channel banks at disturbed and undisturbed locations were compared to elucidate the impact of temperature on terrain configuration.

2.3 Contribution of precipitation to the evolution of the thermokarst

Heavy precipitation in the summer is a major contributor for triggering bank erosion and subsequent mass sediment movement. The cause of the thermokarst evolution is probably a major rainfall event that occurred in July 2003. In the Caribou-Poker Creeks Research Watershed localized precipitation events are a common occurrence and play a significant role in inducing sediment laden surface flows.

Objective: To corroborate the hypothesis, precipitation data were obtained from a rain gauge maintained by the National Atmospheric Deposition Program (NADP; http://nadp.sws.uiuc.edu) located very close the thermokarst site. Additionally water samples were collected at the study sites on the day of some of the major precipitation events and also on the days following them. Discharge analyses were performed and compared with the suspended sediment concentration data and recorded precipitation values.

2.4 Groundwater-surface water interaction

During the early stages of the study, it was observed that there was a difference in discharge rates measured at the upstream and downstream sites. At the downstream site there was a significant reduction in the measured discharge. At the upstream site the water input into the thermokarst was surface flow. But midway through the summer the flow path altered and entered into the active layer. At the downstream site the flow again emerged as surface flow. Subsurface flow is easily transformed into surface flow due to the shallow impermeable permafrost layer. Interflow in the top organic layer was one of the important parameters for sediment transport during the precipitation-free summer periods in 2004 and the time immediately following breakup in 2005.

Objective: To better understand the surface water-groundwater interaction several field observations were conducted to identify potential sub-surface flow paths. Just before the 2005 breakup a Ground Penetrating Radar (GPR) survey was conducted with the aim to identify the potential path of groundwater flow.

All of the aforementioned objectives were selected with the ultimate aim of having a better and clearer understanding of the processes and reasons for the evolution of the thermokarst. To achieve these objectives, extensive and rigorous field work and laboratory analyses were performed over a period of two years.

Chapter 3

Methodology and Field Work

The study site is located in the Caribou-Poker Creeks Research Watershed located about 50 kilometers northeast of Fairbanks, Alaska. Its coordinates are 65°10' N latitude and 147°30' W longitude. The CPCRW is a northeast-southwest trending oval basin about 16 km long and 8 km wide. The watershed is a tributary to the Chatanika River and has a discontinuous permafrost distribution (Slaughter and Lotspeich, 1977). It is the only research watershed in the United States situated in a zone of discontinuous permafrost. Human activity in the watershed is very limited thus providing near pristine conditions for biogeochemical research activities. Soil type in the thermokarst area is predominantly silt loam. Vegetation is typically spruce and an organic mat consisting of moss and low growing shrubs (Rieger et al., 1972). Gradient of the area is mild. Figure 4 shows the location of the thermokarst site and the distribution of permafrost in the watershed (Haugen, 1982). Extensive field studies were conducted during the months of March through October of 2004 and 2005.

3.1 2004 field season

A reconnaissance survey of the study site was conducted on 3/23/2004 to ascertain the general topography of the area and select feasible locations for sample collection. The first point was selected close to the origin of flow previously defined as "upstream site" The second point was selected downstream of the first location, just prior to a pre-existent depression, previously defined as "downstream site". A third location where

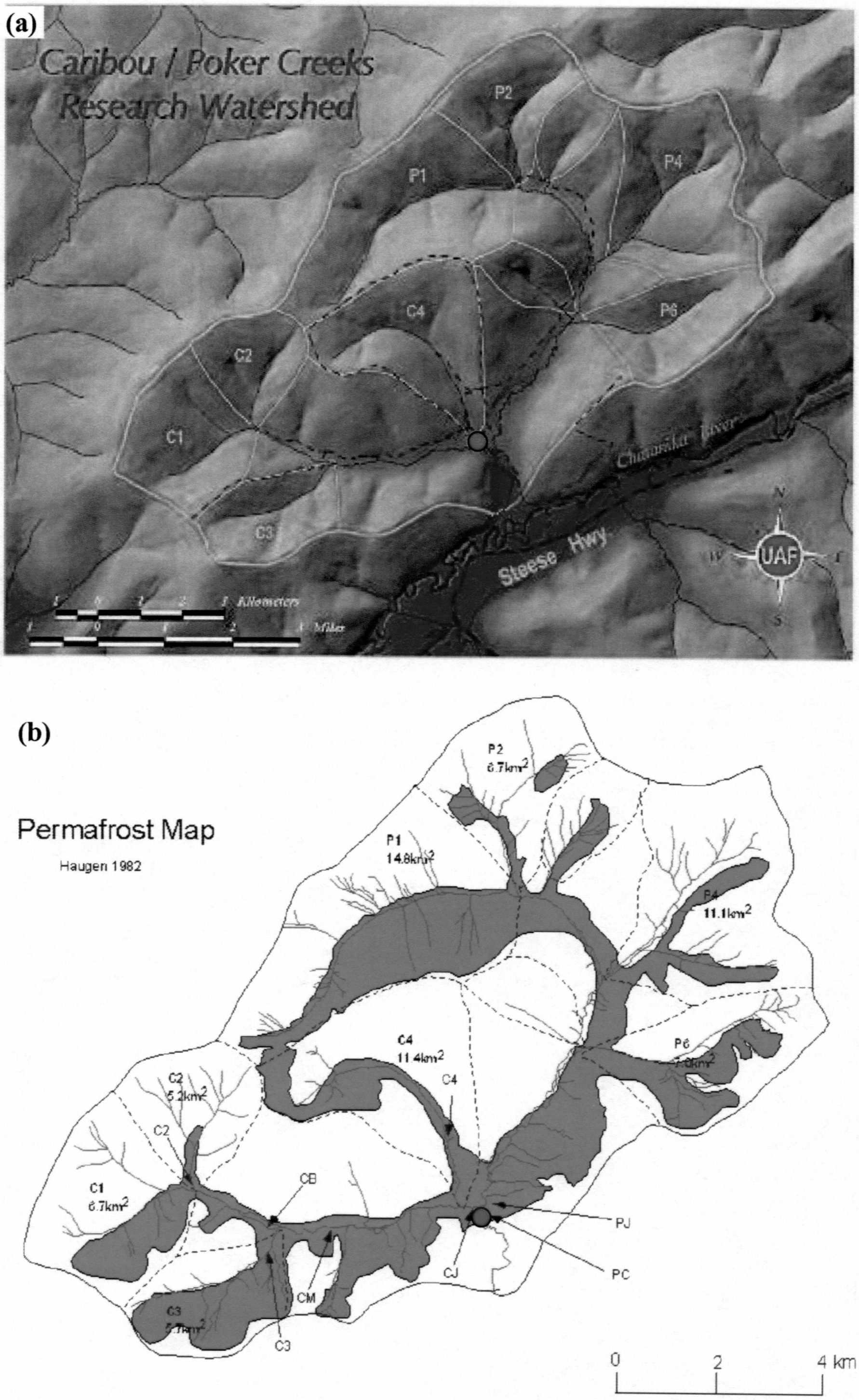


Figure 4. (a) Location of thermokarst site in the Caribou-Poker Creeks Research Watershed indicated by the red dot (http://www.lter.uaf.edu/cpcrw/); (b) Distribution of permafrost in the watershed (Haugen et al., 1982).

bed load transport was observed was also selected for sediment concentration studies. A sediment trap was installed at the downstream site to collect the sediment transported during the breakup season and to also serve as a collection point for water samples and discharge measurements. However, the extremely mobile nature of the thermokarst banks during the course of the study period resulted in frequent changes in the flow direction thereby annulling the utility of the trap for the collection of transported sediment. Towards the end of May, sporadic precipitation events necessitated the installation of an autosampler to collect water samples at predetermined intervals. Two topographical surveys were conducted during the field season; the first one on 5/242004 and the second one on 10/5/2004. Additional field measurements of the thermokarst site were carried out on 8/3/2004 and 9/7/2004. To corroborate the results from laboratory analysis with physical evidence, photographs of major changes to the site were taken at different times during the season.

3.1.1 Sample collection, discharge and suspended sediment concentration studies

Discharge measurements were carried out whenever significant water flow was observed. Due to the uneven terrain and other site constraints the selected discharge measurement method was the volume-by-time method. To reduce human errors introduced during measurements, the procedure was repeated for a minimum of five trials and the average discharge value was calculated and recorded. Water samples were collected in 1000 ml Nalgene® plastic bottles for suspended sediment concentration analysis and particle size distribution studies. In conjunction to the grab sampling, an autosampler ISCO model

3700 was installed in the vicinity of the downstream site near the end of May to capture the flow during flash precipitation events. Samples were collected every 12 hours or 6 hours depending upon the intensity or duration of the precipitation event. An integrated sample was obtained for a day from each bottle in the autosampler. Retrieval of samples and resetting of the autosampler was scheduled every two weeks.

Analysis of the water samples was carried out in the Water and Environmental Research Center (WERC) and Civil and Environmental Engineering Laboratories at the University of Alaska Fairbanks. A batch of twenty water samples were oven dried at 120° C for a minimum period of 24 hours. Due to the very small differences in the sediment concentration values; the dried sediment samples were weighed with a highly accurate analytical balance (4 decimals accuracy). The suspended sediment concentration was then calculated by dividing the weight of dried sediment by the weight of sediment and water and expressed as a dimensional number having the units of mg/g. Grain size distributions were obtained using a particle size analyzer, ELZONE model 5380, available at the WERC labs.

3.1.2 Field surveying

The rapid geomorphologic changes after the substantial rainfall event of July 2003 made it imperative to monitor the changes in the thermokarst. Topographical surveys were conducted at the beginning and end of the 2004 and 2005 field season. The first survey was carried out on 5/24/2004. Benchmarks were selected and marked to serve as a reference for future surveys. The surveyed area incorporated both the study locations and some adjoining regions in anticipation of future surface subsidence. The second topographical survey was performed on 10/5/2004 to assess the growth of the thermokarst from the time of the first survey.

3.2 2005 field season

Continued field studies were scheduled for the 2005 field season. Early in the month of March, a site just adjacent to the downstream site was selected to conduct non-invasive Ground Penetrating Radar (GPR) surveying where piping was observed during the 2004 field season. A 3 m by 3 m area was leveled with the help of a plastic sled. Temperature profiling along the banks at three locations was completed in August and October in order to determine the variation of temperature with depth. Discharge measurements were possible only during breakup as subsurface flow was the primary path of water movement during 2005. Water samples were collected and analyzed for suspended sediment concentration in a similar manner to the 2004 field season. A field survey was carried out on 10/13/2005 to assess the growth of the thermokarst from the previous year.

3.2.1 Temperature profile measurements

In order to assess the temperature variation along the banks two representative sites were selected for temperature profiling. The first site selected was a disturbed site where slumping and erosion were evident. The second site was a relatively undisturbed site with stable banks. Temperatures were measured using a digital thermometer from the channel bed up to the top of the organic layer. The stem of the thermometer was inserted into the soil and the temperature was recorded when a steady reading was obtained. Measurements were carried out in mid-summer, on 8/7/2005, and once again at the start of winter, on 10/13/2005.

Chapter 4

Results and Discussion

A two year study on the evolution of a thermokarst in the Caribou-Poker Creeks Research Watershed was performed. Results from discharge analyses, sediment concentration analyses, and temperature profiling, and observations of some unique cryogenic and geomorphologic processes such as fluvio-thermal erosion, cryogenic piping, bed load transport, sediment deposition process, groundwater flow, and thermokarst evolution, are presented in this chapter.

4.1 Discharge analyses and role of local precipitation

Results from discharge analyses suggest that precipitation events have a great impact on the annual erosion rate in CPCRW (Aldrich and Slaughter, 1982). One of the primary conclusions of a study on the hydrology of thaw lakes in Council, Alaska was the significance of precipitation on the dynamics of the ponds and adjacent terrain (Fraver, 2003). Figure 5 shows the measured discharges at the upstream and downstream study locations for 2004 as well as recorded precipitation. Precipitation values were plotted on the secondary axis. The precipitation values obtained from the NADP rain gauge gave a much better representation of the precipitation affecting the thermokarst site due to the highly localized nature of precipitation in CPCRW.

In 2004, measurable discharge into the thermokarst was first observed on April 24 just after breakup. In general, peak flows were observed the day after a rainfall event indicating a delayed response time at the thermokarst site. During the early part of spring and summer, the water supply to the thermokarst was by snowmelt and rainwater. By mid summer, there was significant discharge even though there was no precipitation. In addition, the discharge at the downstream site was typically lower than the upstream discharge. Both of these factors suggest that subsurface drainage (Hopkins, 1949) in the form of interflow is important in the thermokarst area. The peak flow of 2.05 l/s was recorded on 5/7/2004. The second peak flow occurred on 5/24/2004 and this flow initiated high sediment concentration at the downstream site. No measurable flow was observed after June due to an unusually dry summer 2004.

Discharge data for 2005 at the upstream and downstream sites are presented in Figure 6. Discharge data could only be recorded during the breakup period and for a couple of days after that. The reason for the dearth of discharge data for 2005 is linked to the extensive piping which transformed the flow path from surface flow to groundwater flow. One major difference in recorded data in 2005 was its magnitude compared to that of 2004. Peak flow at the upstream site was 4.65 l/s while the maximum recorded discharge at the downstream site was 5.13 l/s. The higher discharge during the initial flow period acted as a catalyst for higher sediment transport and erosion. In general the discharge pattern exhibits a downward trend with time. Precipitation was absent during each of the discharge measurement days implying that snowmelt was responsible for the water input into the thermokarst.

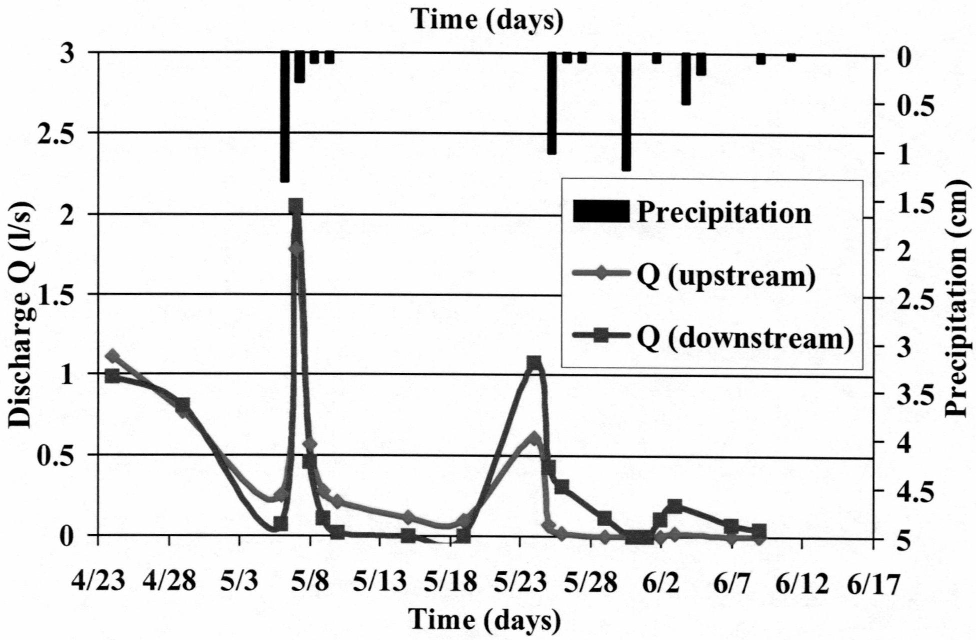


Figure 5. Discharge plot for 2004 at the upstream and downstream sites. Precipitation values are indicated on the secondary axis.

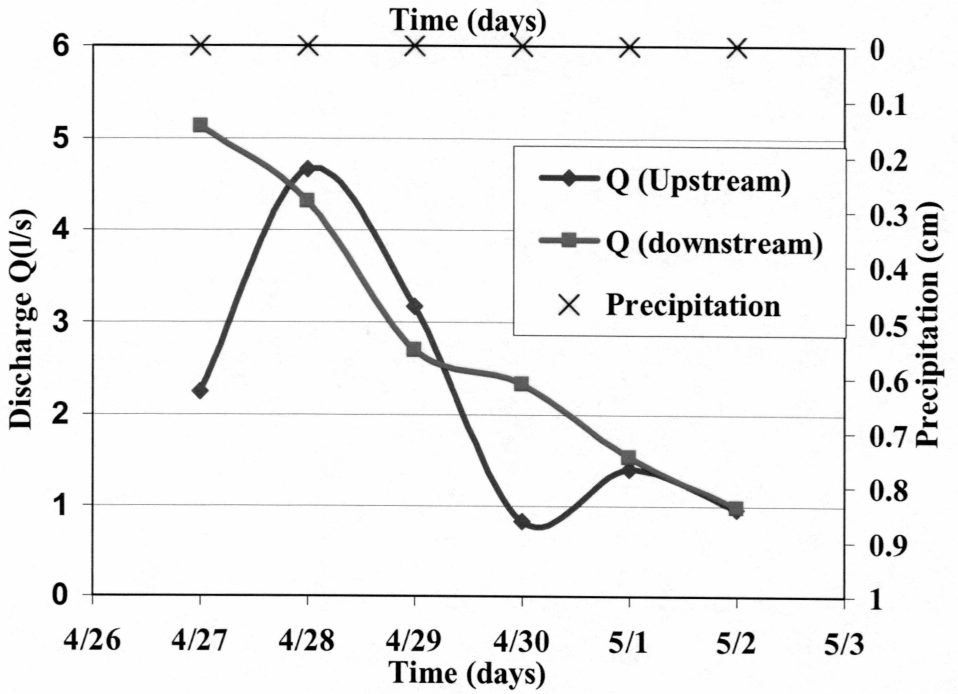


Figure 6. Discharge plot for 2005 at the upstream and downstream sites. No precipitation occurred during the days discharge was measured.

A comparison between the 2004 thermokarst discharge measurements presented in Figure 5 and the 2004 discharge for the C4 watershed located in CPCRW presented in Figure 7 shows very similar trends. The first peak flow for both sites is significantly higher than the subsequent peak flows. A general recession trend in the peak flows is discernable from the plots. During the initial period of the summer the frozen active layer prevents water infiltration into the ground and most of the input flow travels as surface flow. As the summer progresses, the thickening of the active layer enables more water to infiltrate, resulting in a decrease in the overland discharge.

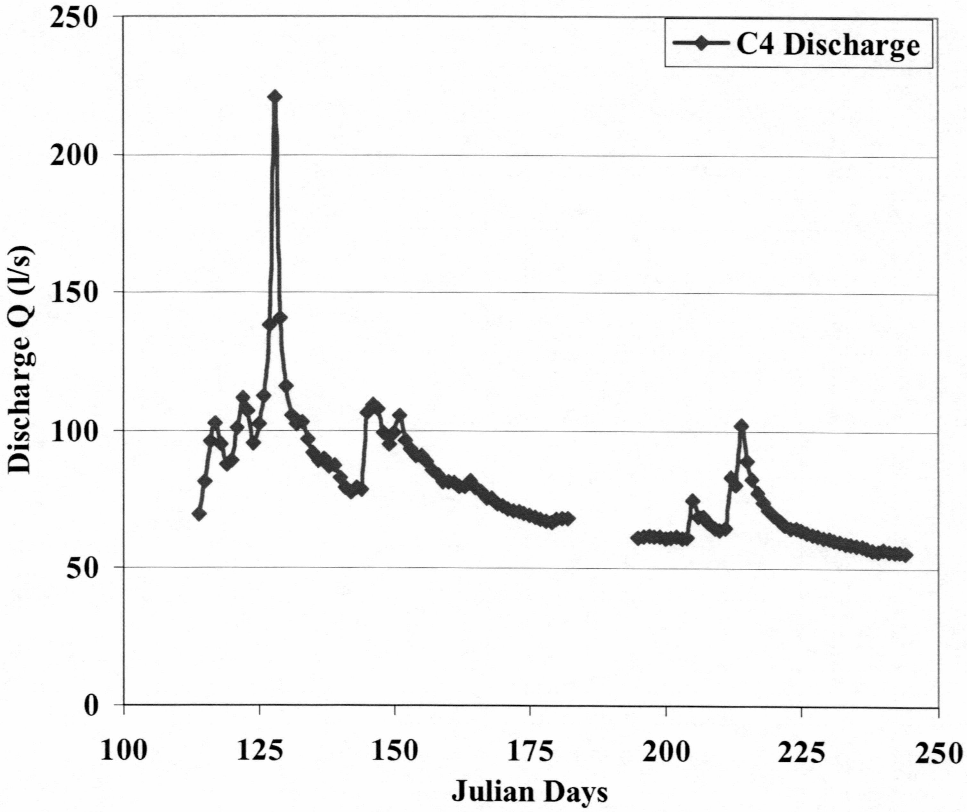


Figure 7. Discharge plot for 2004 at the C4 watershed.

4.2 Suspended sediment concentration analyses

The main objective of the study was to assess and quantify the role of sediment transport in the evolution of the thermokarst. To achieve this, water samples were collected in 1000 ml bottles at the two study sites and analyzed in the laboratory for suspended sediment concentration.

During the middle of the summer in 2004 and 2005 an autosampler was installed in the vicinity of the downstream site to collect daily samples at predetermined intervals. The purpose of measuring daily suspended sediment concentration was to investigate the variability in sediment concentration in time. Results from both *in situ* and autosampler sediment concentration analysis are reported in the following sections.

4.2.1 *In situ* sampling results

The suspended sediment concentration plot for samples collected at the upstream and downstream sites in 2004 are shown in Figure 8. High suspended sediment load was computed after rainfall events, especially during late May and early June. A closer look at the lower left-hand side of the graph confirms that the suspended sediment concentration after snowmelt was very small. Maximum sediment concentration, averaging 40 mg/g, was measured towards the end of May 2004. This sudden spike in the sediment concentration value occurred when the flow path changed from surface water to groundwater. The high pore pressures created during the thaw consolidation process induced soil instability and mass sediment movements. The eroded material from the soil matrix was carried by the flow and deposited in the preexisting depression at the downstream site due to the reduction in the sediment transport capacity. A scale was inserted into the sediment bed as far as possible to measure the depth of sediment infilling. Bed sediment thickness in the pond after the initial deposition was around 60 cm. By the end of summer, following settlement and drying, the thickness was approximately 55 cm.

In 2005 the number of *in situ* samples collected was significantly less than in 2004. Figure 9 shows the suspended sediment concentration plot for the upstream and downstream study locations in 2005. The curves show a similar trend to that observed in 2004. However, higher suspended sediment concentrations were recorded after rainfall events and a gradual reduction in the concentration values was observed towards the middle of summer. One major difference in the data observed in 2004 and 2005 was that the first high sediment concentration recorded in 2005 was almost a month earlier than when that in 2004. Furthermore, in 2004 the downstream sediment concentration values were comparatively higher than the upstream values. But in 2005, both the sites had similar concentration values for most of the samples. In 2004 the high sediment flow was taking place only at the downstream site. However, in 2005, both the upstream and downstream sites witnessed rapid geomorphologic changes. The plots are represented with dotted lines since data were unavailable for the middle portion of May and June of 2004. The peak suspended sediment concentrations for the upstream and the downstream sites were 44.40 mg/g and 44.81 mg/g, respectively. In 2004 the average suspended sediment load, defined as the product of water discharge and sediment concentration, at the upstream site was 0.26 mg/s and at the downstream site was 2.17 mg/s. In 2005, the suspended sediment load at the upstream site was 5.83 mg/s and at the downstream site was 2.94 mg/s indicating more sediment volume at the upstream site in 2005.

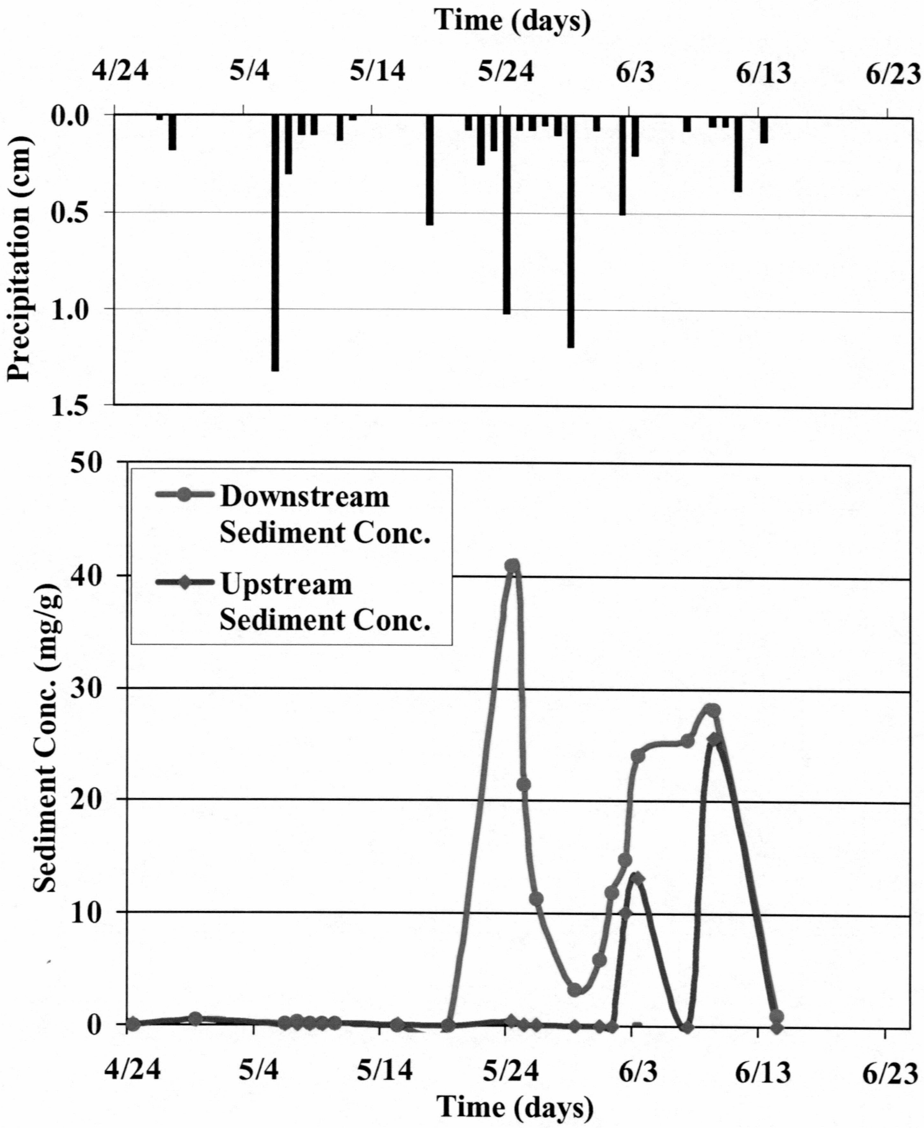


Figure 8. Suspended sediment concentration plot for 2004 at the upstream and downstream sites.

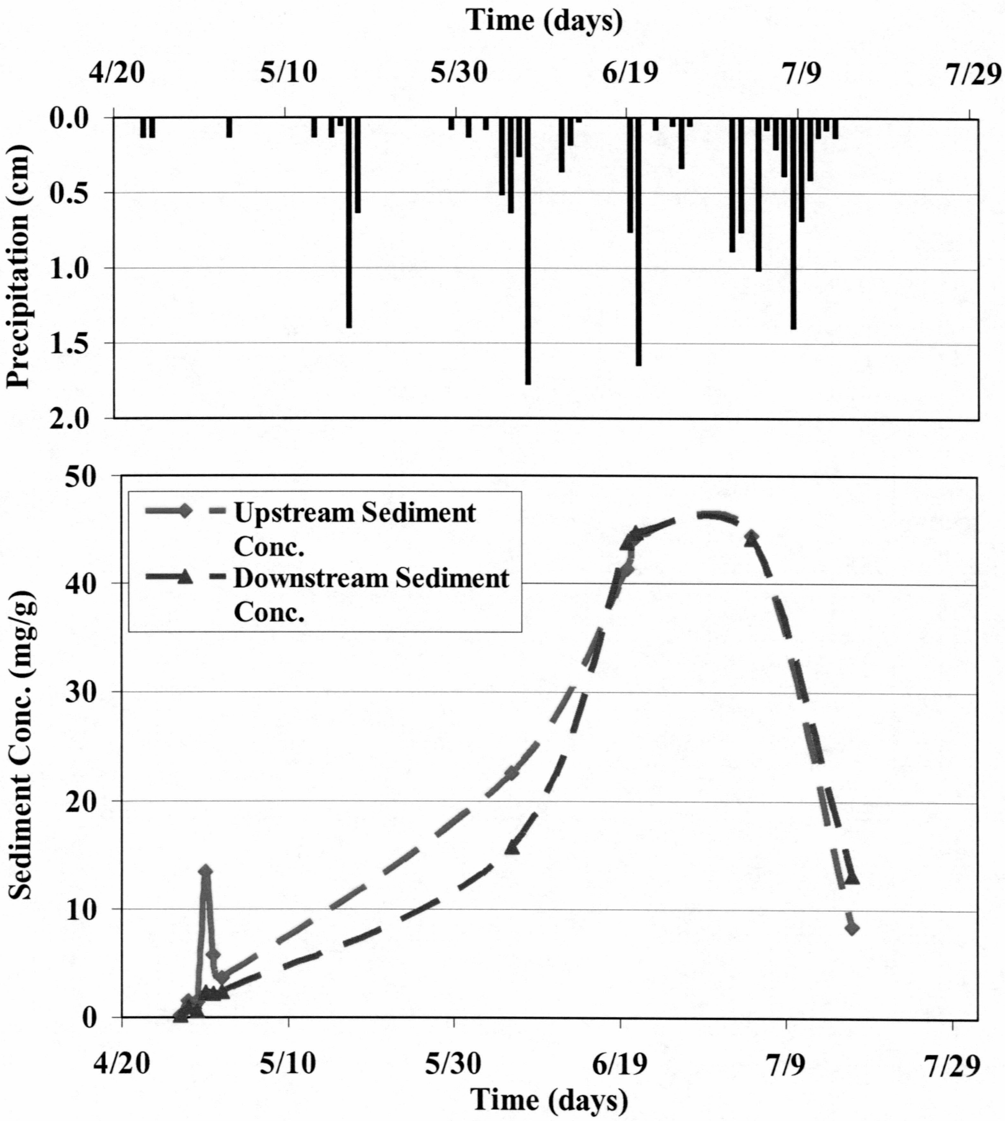


Figure 9. Suspended sediment concentration plot for 2005 at the upstream and downstream sites.

4.2.2 Autosampler sampling results

An ISCO® 3700 autosampler was installed to collect water samples at 6 hour intervals. Thus for a day an integrated sample was obtained. Figure 10 shows the location where the autosampler was installed in 2004. Even during periods of low flow, the autosampler continued to operate to capture the flow due to flash rainfall events.

Figure 10. Location of the installed autosampler for collecting samples during 2004.

Figure 11 shows a plot of the suspended sediment concentration of samples collected during 2004 and Figure 12 indicates a graph of the suspended sediment concentration values for samples collected in 2005. Higher concentration values were measured in 2004 and 2005 during the initial period of operation of the sampler. Both plots show a general decreasing trend with time due to decreasing sediment transport capacity.

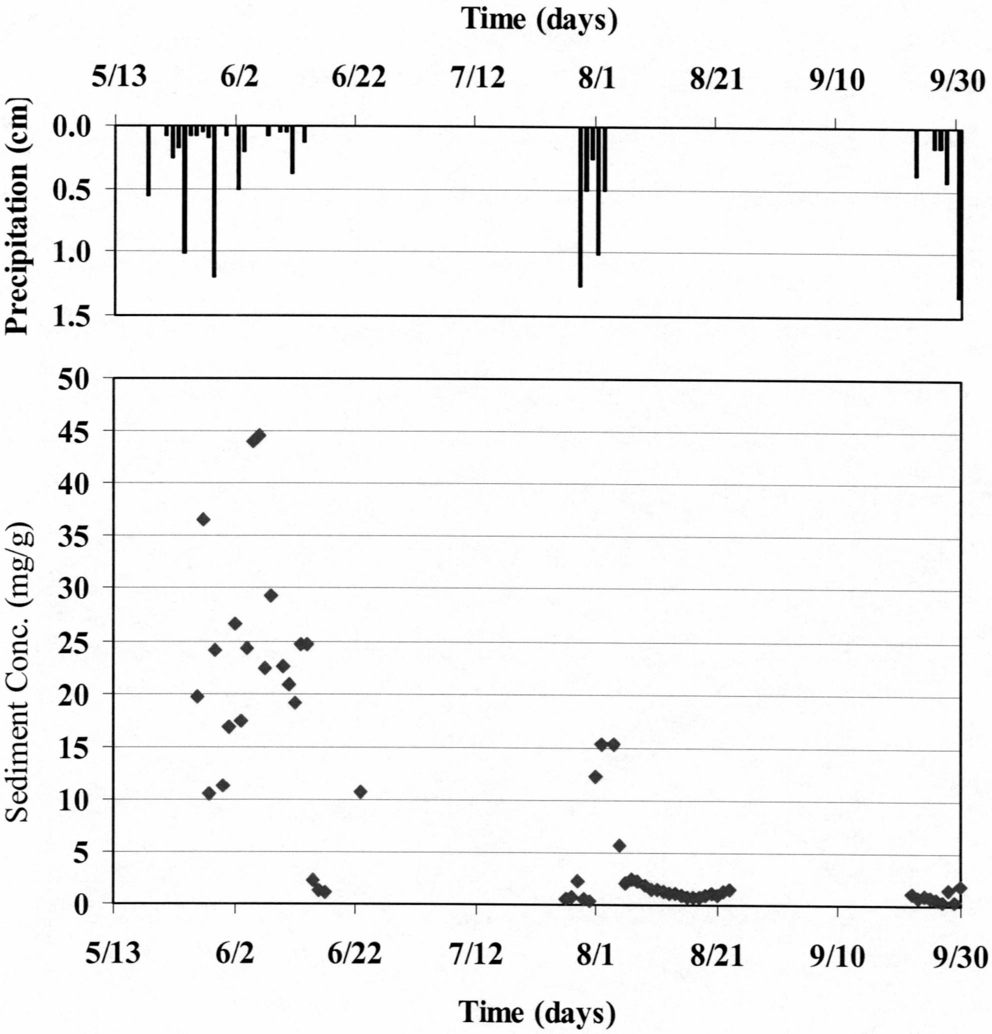


Figure 11. Suspended sediment concentration plot for 2004. The samples were obtained from the autosampler.

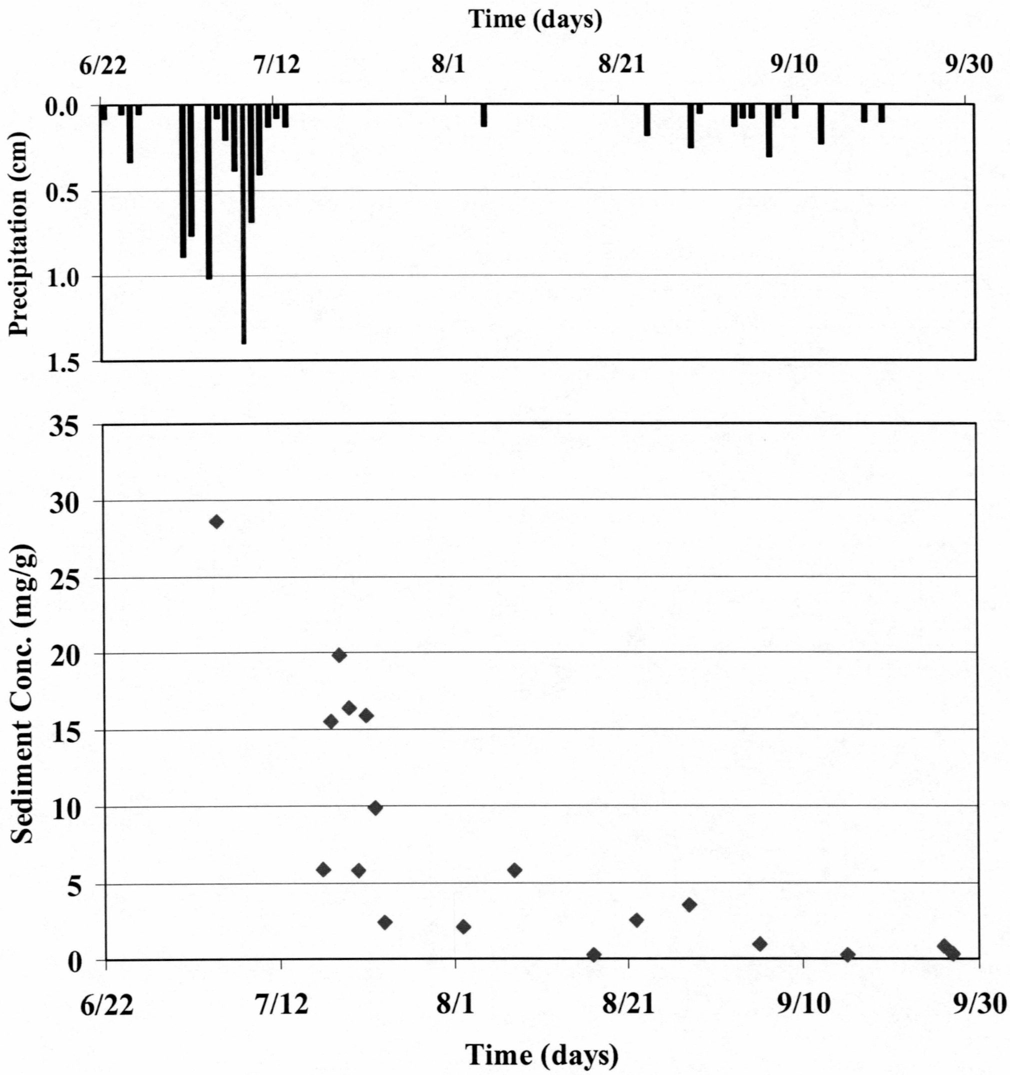


Figure 12. Suspended sediment concentration plot for 2005. The samples were obtained from the autosampler.

4.3. Particle size analysis

Particle size analyses of the dried sediment samples were performed to assess the type (size) of sediment transported at different periods during the field season of 2004. Results from the particle size analyses are presented in Figure 13. Four different sediment samples were collected; one from a water sample taken after snowmelt; the second taken when there was a peak rainfall event; the third taken when high sediment flow was first observed, and the fourth taken during a period of low discharge. The data indicate that during snowmelt, the sediment sizes in suspension were very small compared to sediment in suspension during the later periods. The curves progressively shift towards the right, thus suggesting a general increase in the particle size with time. However, by mid summer, the curve again shifts to the left due to lower flows, suggesting a reduction in sediment transport capacity.

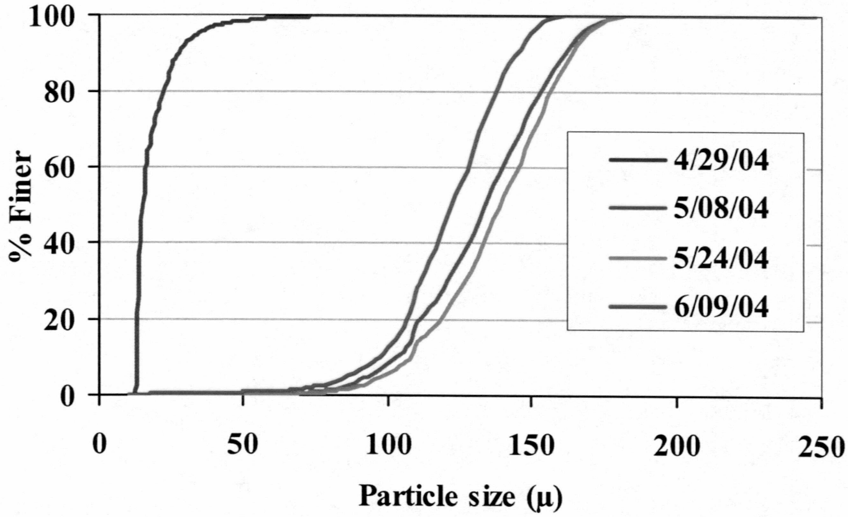


Figure 13. Particle size distribution analyses curves of suspended sediment samples.

4.4 Fluvio-thermal erosion

Whenever flowing water is in contact with ice-rich soils, rapid and extensive degradation of the landform occurs (Dingman, 1976). Ground subsidence and increased thermokarst development is amplified by thermal erosion associated with the flowing water (U.S. Arctic Research Commission Permafrost Task Force, 2003). The combined effect of flowing water and thermal abrasion is known as fluvio-thermal erosion. The undercutting associated with the flowing water causes the formation of 'thermoerosional niche'. This phenomenon is usually seen along circumpolar river banks (French, 1996; Walker et al., 1987; Czudek and Demek, 1970). However, the presence of ice-rich permafrost at the water level induced conditions for the development of a thermoerosional niche and its subsequent collapse at CPCRW.

One of the main factors for the high rate of lateral erosion detected at the upstream site during the 2004 field season was due to the combined erosive effects of flowing water and permafrost thaw. In this process, the bank erosion was more pronounced due to the dual action of mechanical abrasion of flowing water and thawing of the underlying permafrost. The presence of unconsolidated sediment, for instance silt loam, caused the formation of thermo-erosional niche structure. The undercutting due to the standing water was of the order of 20 cm. The undercutting progressed along with sediment removal until the block became unstable and sheared off. Thawing of the permafrost was of a higher magnitude following the block failure of the thermo-erosional niche (Walker and Arnborg, 1963). Figure 14 (a) is a modified schematic representation of a thermo-erosional niche adapted from French, 1996. Figure 14 (b) presents a photograph of a niche-like feature at the upstream site that eventually failed at the water level. Figure 14 (c) shows the eroded ice rich sediment deposited at the bottom of the niche. Figure 14 (d) is a photograph of the failed block which sheared off the bank due to instability.

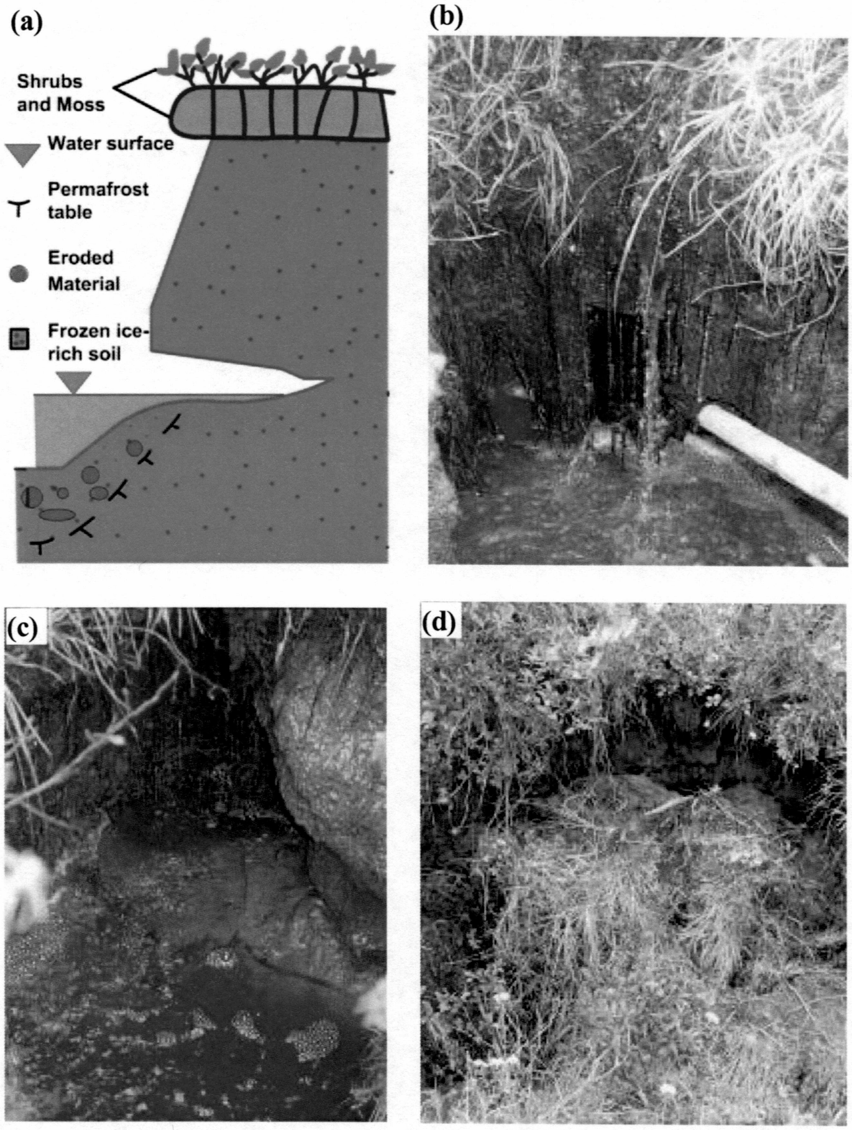


Figure 14. Erosion process occuring at the upstream thermokarst location. (a) schematic depiction of a thermo-erosional niche (from French, 1996); (b) thermo-erosional niche-feature at the upstream site. The shovel shows the undercutting due to water flow; (c) eroded sediment deposited at the bottom of the channel; (d) block failure of the niche due to instability.

4.5 Bed load transport and sediment deposition process

In the outlying downstream reach of the thermokarst distinct patterns (ripples) of fine sand were formed after the 2004 breakup and the first major precipitation event, indicating bed load transport. High flow after breakup and the initial rainfall event enabled fines to be entrained in the water. Unique patterns of fine sand were observed at this site on 4/29/2004 and 5/07/2004. The first photograph in Figure 15 depicts the bed load pattern observed just after breakup and the second photograph shows the pattern of fines moving along the bed following the initial high rainfall event. No bed load transport was observed later on in the summer due to very low discharge in the thermokarst.

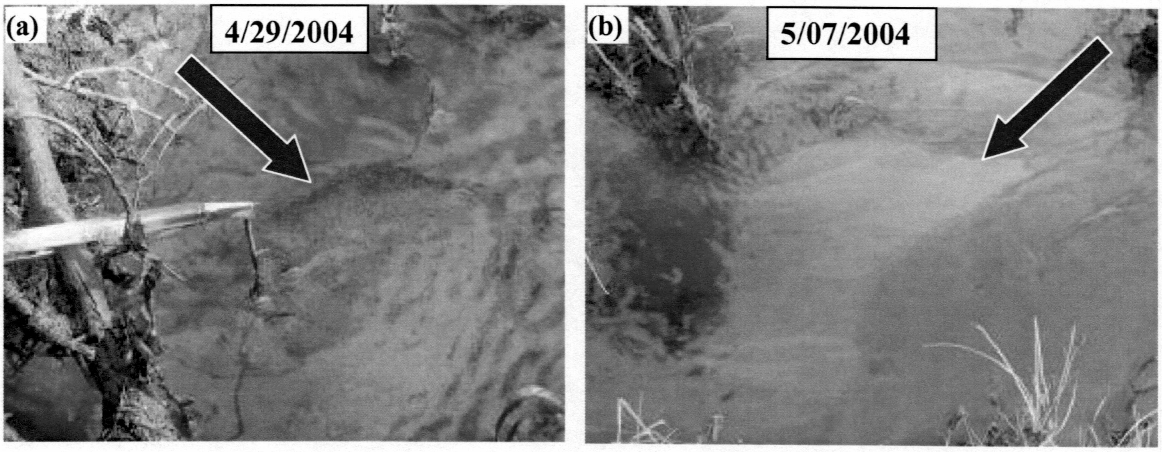


Figure 15. Bed load transport forms (ripples) observed in 2004 at the thermokarst site. (a) pattern of fine sand observed on 4/29/2004 following breakup; (b) bed load transport pattern seen on 5/07/2004 after the first major precipitation event.

Water samples were collected at the bed load transport site during 2004 whenever high rainfall was recorded. The samples were analyzed in the laboratory for suspended sediment concentration. The suspended sediment concentration values obtained at the bed load transport site were compared to the sediment concentration values measured at the downstream site. Table 1 shows the suspended sediment concentration values at the two sites measured on 5/24/2004 and 5/26/2004 when significant precipitation occurred in the vicinity of the thermokarst.

Table 1. Comparison of suspended sediment concentration values at the upstream site and downstream site.

	Upstream site	*Downstream site*
Date	**Suspended Sediment Concentration (mg/g)**	**Suspended Sediment Concentration (mg/g)**
5/24/204	40.92	11.86
5/26/2004	11.3	6.84

Comparison of the suspended sediment concentration values brought to light a very interesting phenomenon in the reach between the upstream site and the bed load transport site. On 5/24/2004, following a rainfall event, the surface water was introduced at the upstream site and was running along the entire thermokarst. Flow velocity was reduced due to the depression acting as a buffer. The lower velocity enabled sediment to settle in the depression. The remainder of the sediment in suspension was carried downstream. The suspended sediment concentration at the downstream site was 40.92 mg/g and at the bed load transport site was 11.86 mg/g. This indicated that approximately 75% of the sediment load was retained in the downstream depression and only a small fraction was transported downstream. However, on 5/26/2004, the suspended sediment concentration value at the downstream site was 11.3 mg/g and at the bed load transport site it was 6.84 mg/g. In this instance more than 60% of the available sediment was carried downstream while only a small fraction was retained in the downstream depression. The previously deposited sediment reduced the volume of the depression, and thus the velocity of the flowing water was reduced to a lesser extent than was observed on 5/24/2004. Higher velocity prevented settling in the downstream depression and transported a higher quantity of the sediment to the bed load transport site. Figure 16 shows a schematic sequence of events following the two rainfall events and the corresponding sediment transported and deposited at the two sites.

This phenomenon is commonly seen in reservoirs constructed across major rivers to store water for hydroelectric power generation and irrigation purposes. The above described process, when applied to reservoirs, is termed reservoir sedimentation. Reservoir sedimentation affects the sediment trap efficiency of the reservoir by reducing the available storage volume (see for instance, Toniolo and Schultz, 2005). The occurrence of this process in the thermokarst implies that fluvial processes can occur not only in man made structures but also in cryogenic structures like thermokarsts unique to high latitude arctic regions.

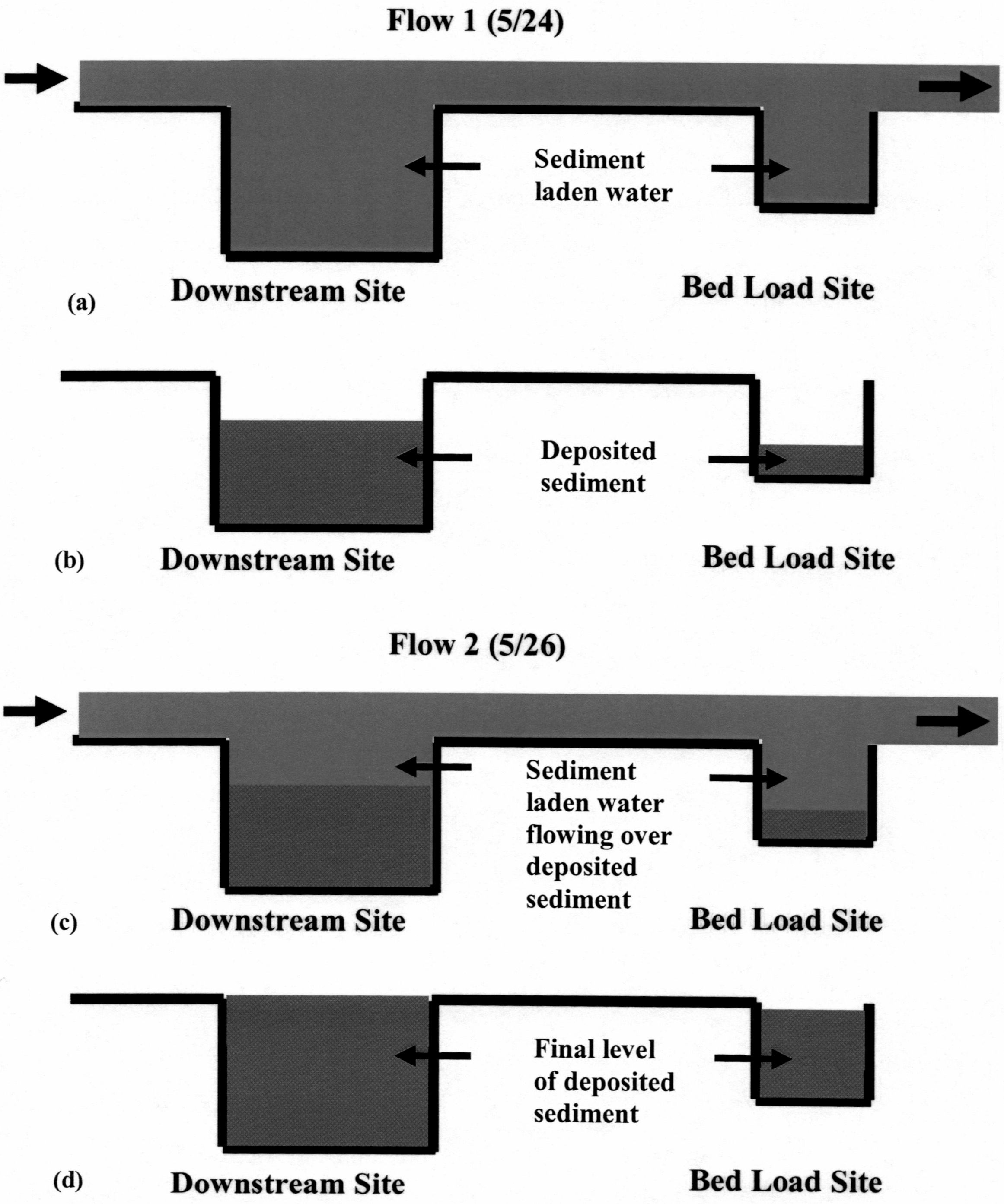


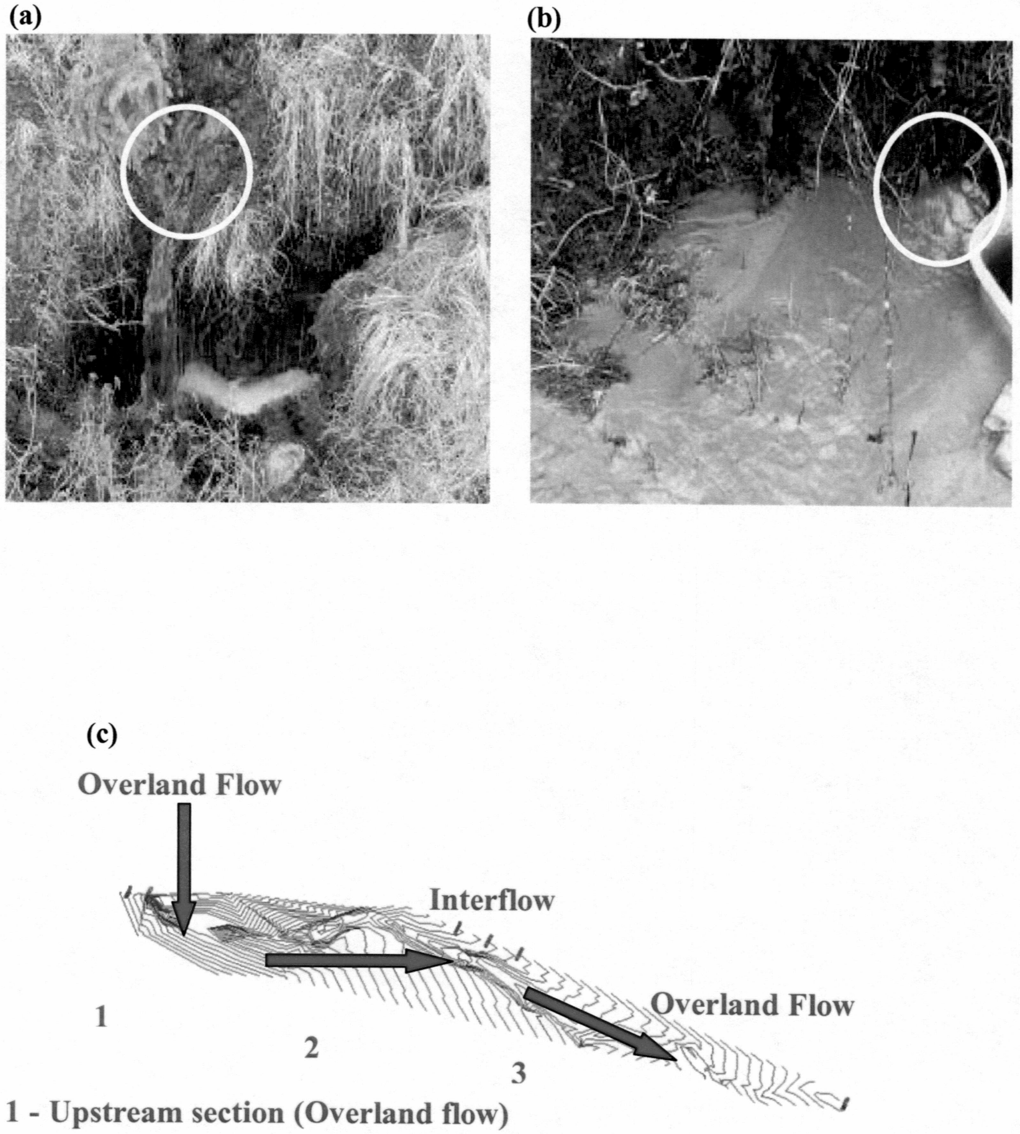
Figure 16. Schematic sequence of events of sediment transport and deposition following two rainfall events in 2004 (a) and (b) show the sediment flow and deposition on 5/24/2004; (c) and (d) show the sediment flow and deposition on 5/26/2004. Figures are not to scale.

4.6 Groundwater flow investigation

Evidence of groundwater flow in regions underlain by discontinuous permafrost has been assessed in the Canadian Yukon Territory (Brandon, 1966), from field observations and oil borings. No conclusive results were obtained in a study of subsurface flow utilizing a barrier between the surface and active layer (Soulis and Reid, 1978). More recently a ground penetrating radar (GPR) technique has been employed to map the subsurface structure and detect voids (Davis and Annan, 1989). Studies conducted near Council, Alaska have shown that GPR and DC resistivity methods can detect the presence of shallow talik formations and permafrost thickness (Yoshikawa and Hinzman, 2003). Ground penetrating radar is a non-invasive geophysical method which can be used to map the near-surface (Hubbard et al., 1997) and subsurface sedimentary structures (Peretti et al., 1999) of the earth. High frequency electromagnetic waves are transmitted by moving a transmitter unit over a level ground surface and the reflected waves are captured by a receiving antenna (Knight, 2001).

Groundwater flow was evident at the thermokarst site during 2004 when discharge was recorded even during prolonged periods without precipitation events. Figure 17(a) shows the flow at the upstream site through the vegetation mat, which can be classified as overland or surface flow. Overland flow was observed in the early summer and it occurred due to the rapidly melting snow pack (Lewkowicz, 1983). In the intermediate section of the thermokarst, the flow was within the active layer indicating interflow. In the downstream site, the flow emerged through the active layer as shown in Figure 17(b) where the flow again changed to overland flow. There are some indications that, due to the massive sediment transport underground, subaerial forms such as funnel shaped pits may have formed (Czudek and Demek, 1970). Figure 17(c) shows a thermokarst contour plot illustrating the different sections and the estimated type of groundwater flow associated with each section.

The unsaturated zone or the vadose zone is the layer of soil where the water pressures are less than atmospheric. It is composed of pore spaces that contain some air and some water. Water in the unsaturated zone that flows laterally to a surface body is known as interflow (Fitts, 2002). Interflow infiltrates the subsurface and may be deflected horizontally by low permeability layers in the unsaturated zone. The permafrost present beneath the thermokarst depression acts like an impermeable barrier to water infiltration. Cryogenic piping observed during 2005 was a result of the lateral flow. Due to the high pore pressures, the ice rich soil was washed away with the infiltrated water and was transported through the pipes and again transformed into surface flow at the preexisting depression. It is assumed that the permafrost table is very close to the level of the piping. In some instances at the upstream end, even though piping was not evident, there was bubbling observed in the depression. A complex flow pattern for the interflow was observed, suggesting the flow direction varied as the permafrost degraded. One major implication of the downward movement of water in the summer from the surface to the active layer is the change in geocryologic conditions (Mackay, 1983) evidenced by the significant change in the thermokarst site evolution.



1 - Upstream section (Overland flow)

2 - Intermediate section (Interflow)

3 - Downstream section (Overland flow)

Figure 17. Groundwater flow observations at the two study sites in the thermokarst (a) overland flow observed at the upstream section; (b) flow through the active layer at the downstream section; (c) contour plot and estimated flow path.

Subsurface investigations using the GPR survey were partially successful. Results from the GPR survey failed to provide conclusive evidence for the interflow path. GPR performance was inhibited due to the higher electrical conductivity of the predominantly silt soil present in the vicinity of the thermokarst, which has also been mentioned in previous field experiment reports (Davis and Annan, 1989). However, the GPR reflection image shown in Figure 18 revealed the presence of an unfrozen pocket at the active layer permafrost table boundary. The unfrozen pocket of water was located at a depth of approximately 1 m below the ground surface at the active layer/permafrost interface with the permafrost acting as an impermeable barrier (Kane and Slaughter, 1973).

The unfrozen groundwater, also known as suprapermfrost water (Dingman, 1976), detected by the GPR survey indicates that the active layer did not completely freeze during the 2004 winter. The presence of the unfrozen pocket of water indicates a lowering of the permafrost table due to its degradation.

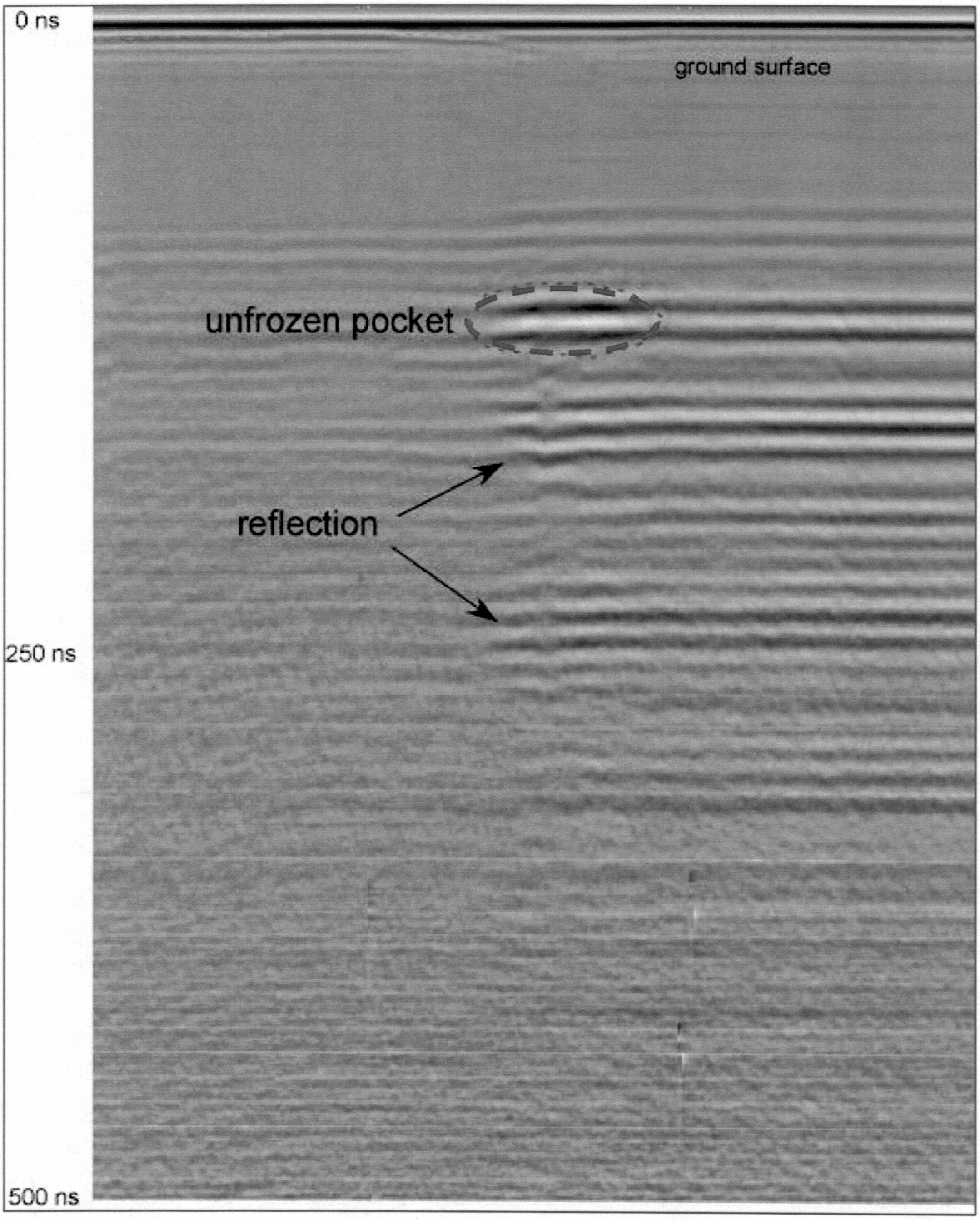


Figure 18. GPR reflection image showing the unfrozen water pocket at the active layer – permafrost boundary. The dotted red line at the top of the image represents the ground surface.

4.7 Cryogenic piping and sediment transport

The presence of subsurface water flow, though not physically evident, was hypothesized since the beginning of the study in 2004, when high sediment flows were noticed from pipe formations at the downstream site. In 2005, the piping phenomenon was observed at the upstream site and in the intermediate section between the upstream site and downstream site. Water movement downslope from the point of initiation of the piping was near surface flow or interflow, which usually transpires in an organic mat with high porosity (Hinzman et al., 1991). Special circumstances such as the presence of buried ground ice warrant the formation of subsurface outlets for water drainage (Harry and French, 1983). Thawing of ice rich soil also occurs when the surface water infiltrates the active layer, which may further lead to subterranean erosion. It has been suggested that thermokarst regions may be highly prone to subaerial structures and formations (Czudek and Demek, 1970). Formation of the cryo-pipes enlarged the preexistent thermokarst depressions at the two study sites. Similar observations have been reported in some studies conducted in Fairbanks, Alaska (Péwé, 1982).

The cryo-pipe in the study area was exposed when rapid erosion progressed upwards from the upstream site. At the peak of its development, the outer pipe diameter was approximately 50 cm while an inner pipe had a diameter of around 10 cm. The improved drainage capacity of these pipes (Holden, 2005) transported a significant amount of the groundwater to the downstream site. Figure 19 depicts the sequence of photographs from origin to collapse of the cryogenic pipe.

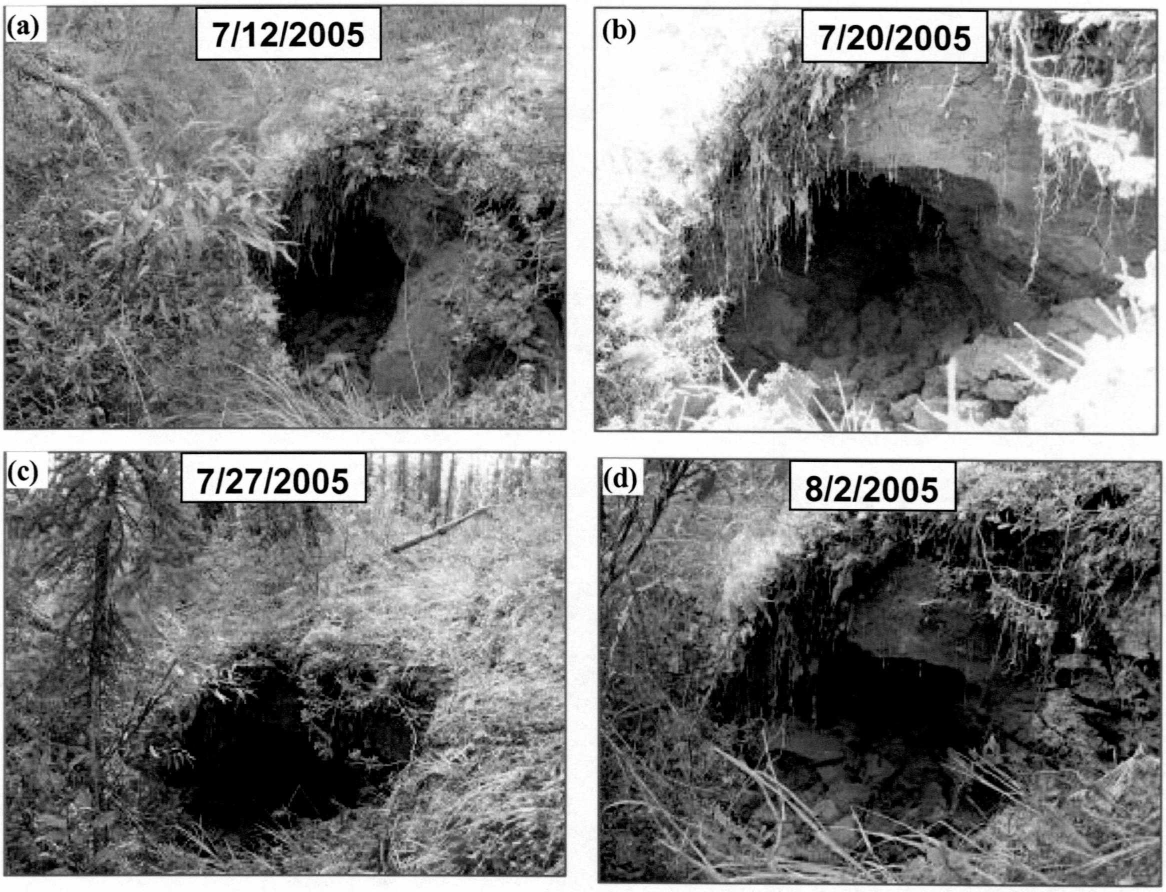


Figure 19. Cryogenic pipe genesis and subsidence sequence. (a) initial exposure of the pipe; (b) pipe enlargement and start of erosion; (c) advanced stage of pipe subsidence; (d) final state of the collapsed pipe with eroded material covering the pipe entrance.

The whole sequence of pipe exposure, enlargement, and ultimate collapse was recorded from the middle of July 2005 to the beginning of August 2005. A couple of precipitation events that occurred during the first half of July 2005 also contributed to the rapid transformation and development of the pipe.

A close up view of the exposed sediment shows an ice rich sediment structure in the initial stages of pipe exposure. Following erosion and collapse, the entrance of the pipe was completely filled with eroded material. The close up views of this sequence are presented in Figure 20.

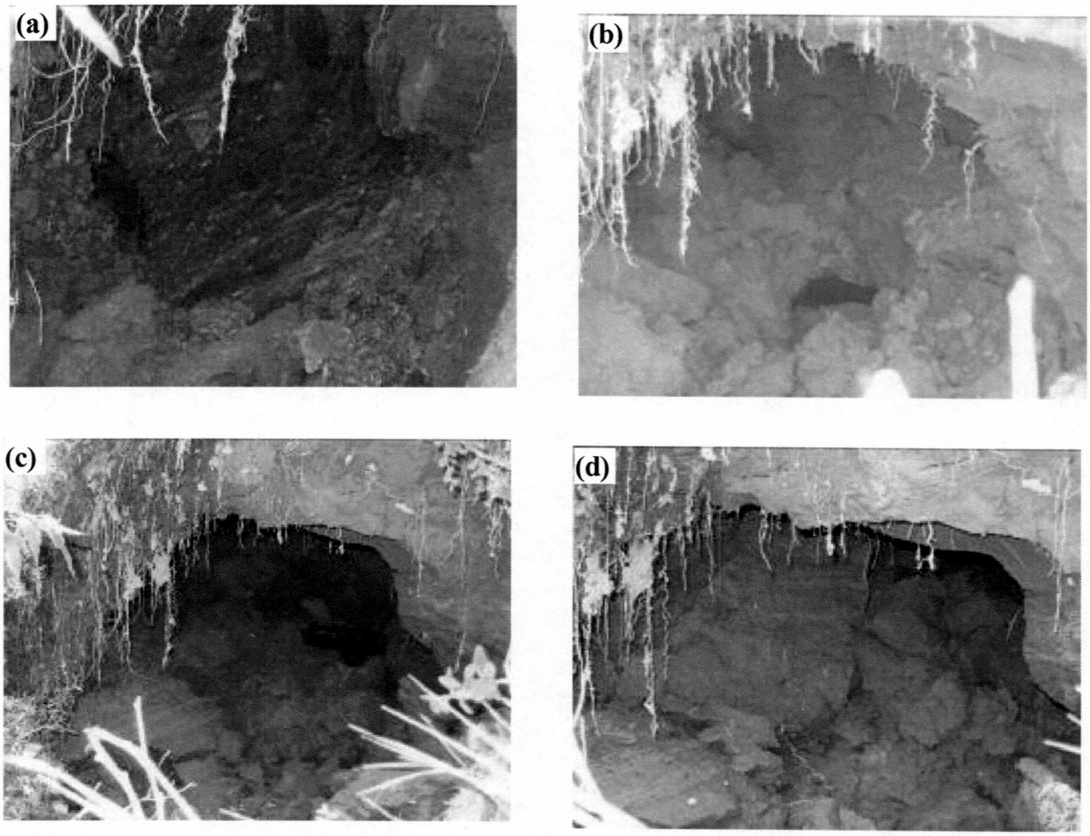


Figure 20. Close up view of the cryogenic pipe depicting the exposure and ultimate erosion of ice rich soil. (a) ice rich soil at the beginning of pipe exposure; (b) erosion of the sediment from the sides of the pipe; (c) advanced stage of sediment erosion and deposition; (d) collapse of the walls and sediment cave in.

4.8 Temperature profiling in the thermokarst

In order to profile the temperature variation along the banks of the thermokarst subjected to different intensities of erosion, two sites were selected for observation. The first site was a disturbed site where slumping was pronounced. The second site was an undisturbed site where the banks were stable. Surface temperature profiles were measured along the left and right banks on 8/7/2005 and 10/13/2005. Results shown in Figure 21 and Figure 22 indicate that the temperature gradient at the disturbed site was steep (8 °C variation in 1 m) in August, but that there was a more uniform temperature profile in October. The undisturbed site had uniform temperature profiles during each of the measurements.

One plausible explanation for the steep temperature gradient at the disturbed site is the drying of the eroded bank material, which can impact the latent and sensible heat flux movements (Yoshikawa and Hinzman, 2003). A secondary explanation could be the difference in thermal conductivities of the organic layer and the underlying soil. Furthermore, contact with the flowing water at the undisturbed site strongly influenced the soil moisture content, which controls the soil thermal properties (Waelbroeck, 1993) and the higher thermal gradient at the surface (Brewer, 1958). The curvature in the disturbed site temperature profile is due to the presence of unfrozen water at the base of the channel (Osterkamp and Romanovsky, 1999). The temperature profile study was limited to observe the variation in temperature at the disturbed and undisturbed sites. Detailed thermal analysis was beyond the scope of the present research.

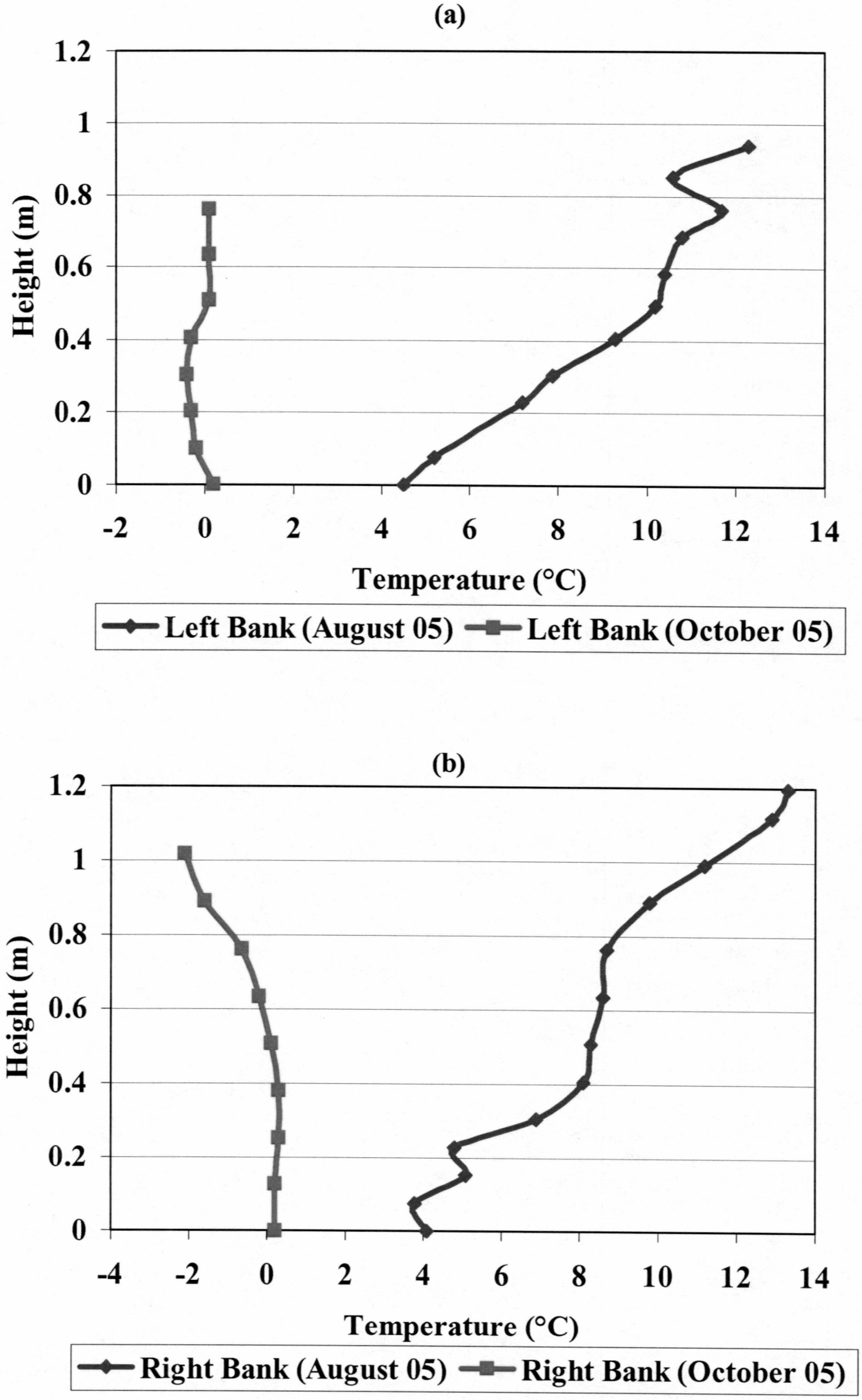
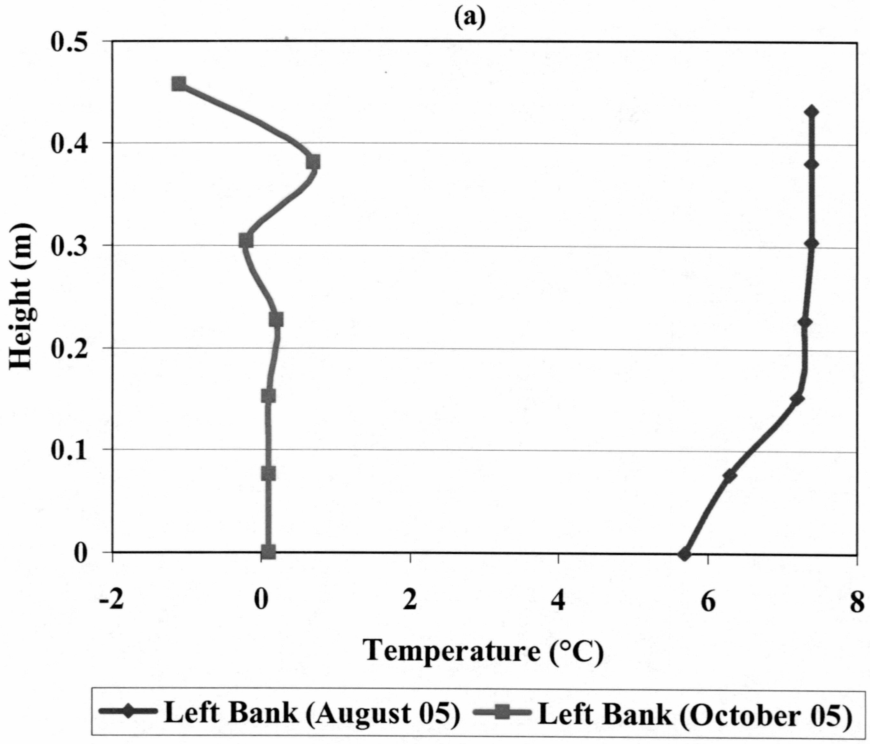


Figure 21. Temperature profiles at the disturbed site measured on 8/7/2005 and 10/13/2005. (a) left bank temperature profile; (b) right bank temperature profile.



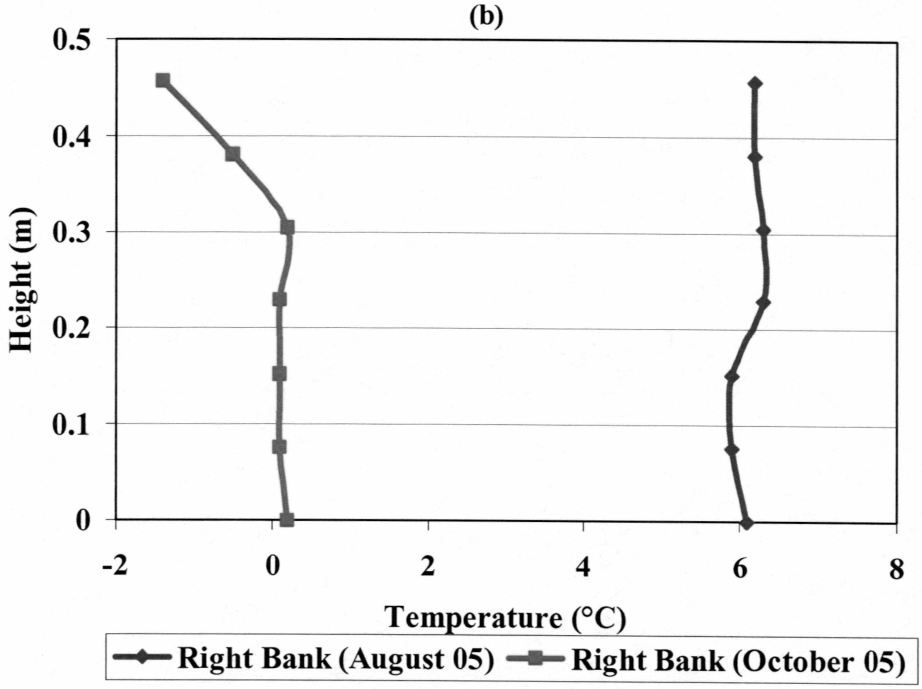


Figure 22. Temperature profiles at the undisturbed site measured on 8/7/2005 and 10/13/2005. (a) left bank temperature profile; (b) right bank temperature profile.

4.9 Thermokarst evolution

Contrary to the notion that dry summers inhibit the growth of thermokarst and thermokarst lakes (Bosikov, 1998), the thermokarst in CPCRW experienced significant evolution and growth during a dry-warm 2004 summer. Evolution of the preexistent depressions, also known as a gully (Istanbulluoglu et al., 2005) progressed rapidly with sediment infilling and bank retreat. The gully erosion supported mass wasting of the sediment in the mild gradient thermokarst site, which was surprising because such high sediment outwash normally occurs in regions having steep gradients (Aldrich, 1979). Additionally, the recurrence of surface disturbance negated the assumption that the magnitude of erosion decreases with the amount of time after the initial disturbance.

4.9.1 Thermokarst growth in 2004

Drastic morphologic changes were evident in the entire study area. Figure 23 and Figure 24 show the evolution at the upstream and downstream locations, respectively, from the start of spring till the end of summer of 2004. At the upstream location, erosion along the banks was substantial as indicated by Figure 23(a) and by the end of summer a new channel had developed in the reach as evidenced in Figure 23(b).

Figure 24 illustrates the sequence of events that were observed at the downstream site in 2004. There was significant water discharge after breakup (4/29/004 photograph) followed by erosion along the banks (5/15/2004 photograph). Muddy water is clearly noticeable in the photograph taken on 5/24/2004. The sediment filled depression in a dried state at the end of summer is shown in the photograph taken on 8/13/2004.

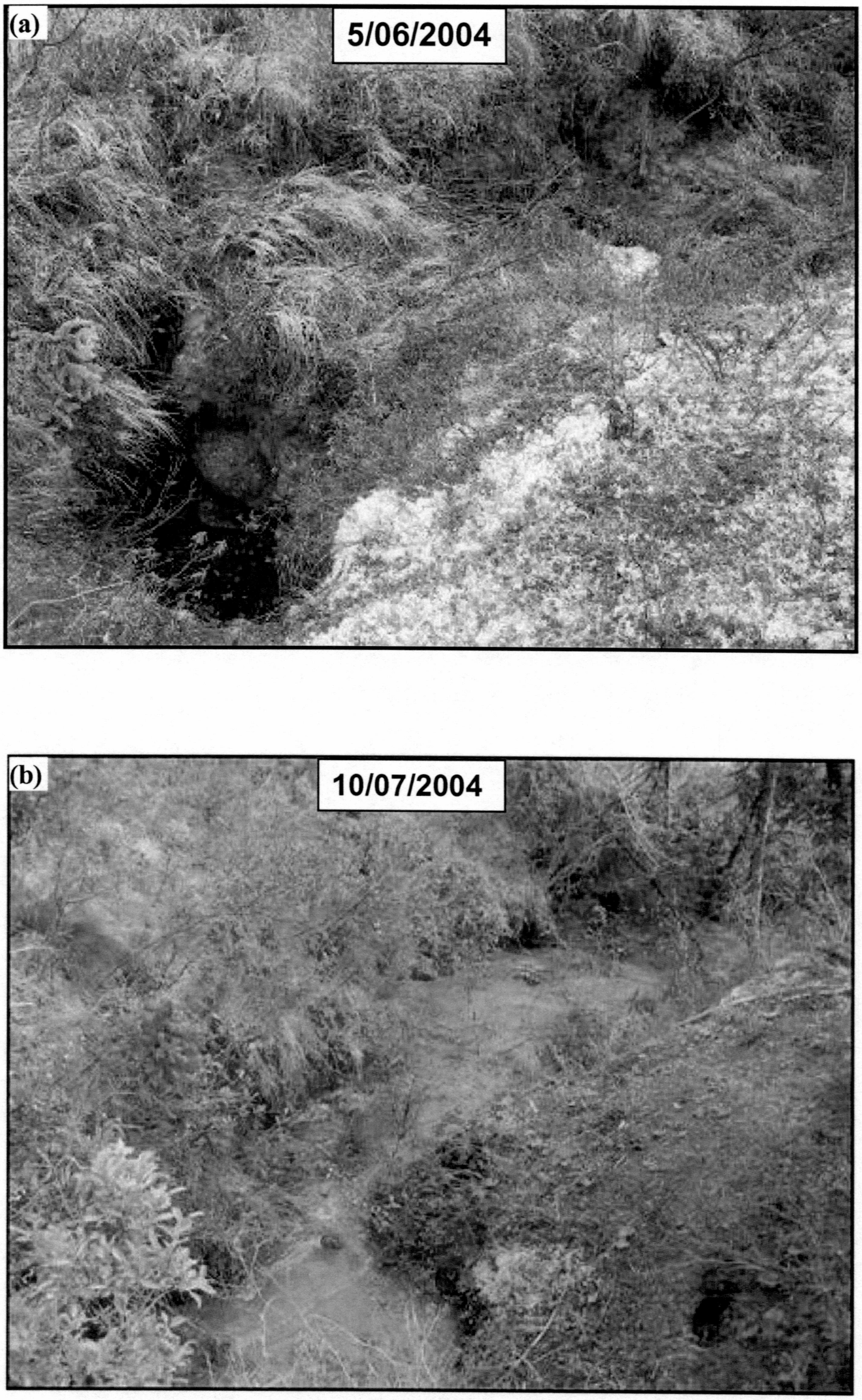


Figure 23. 2004 thermokarst evolution observed at the upstream site.

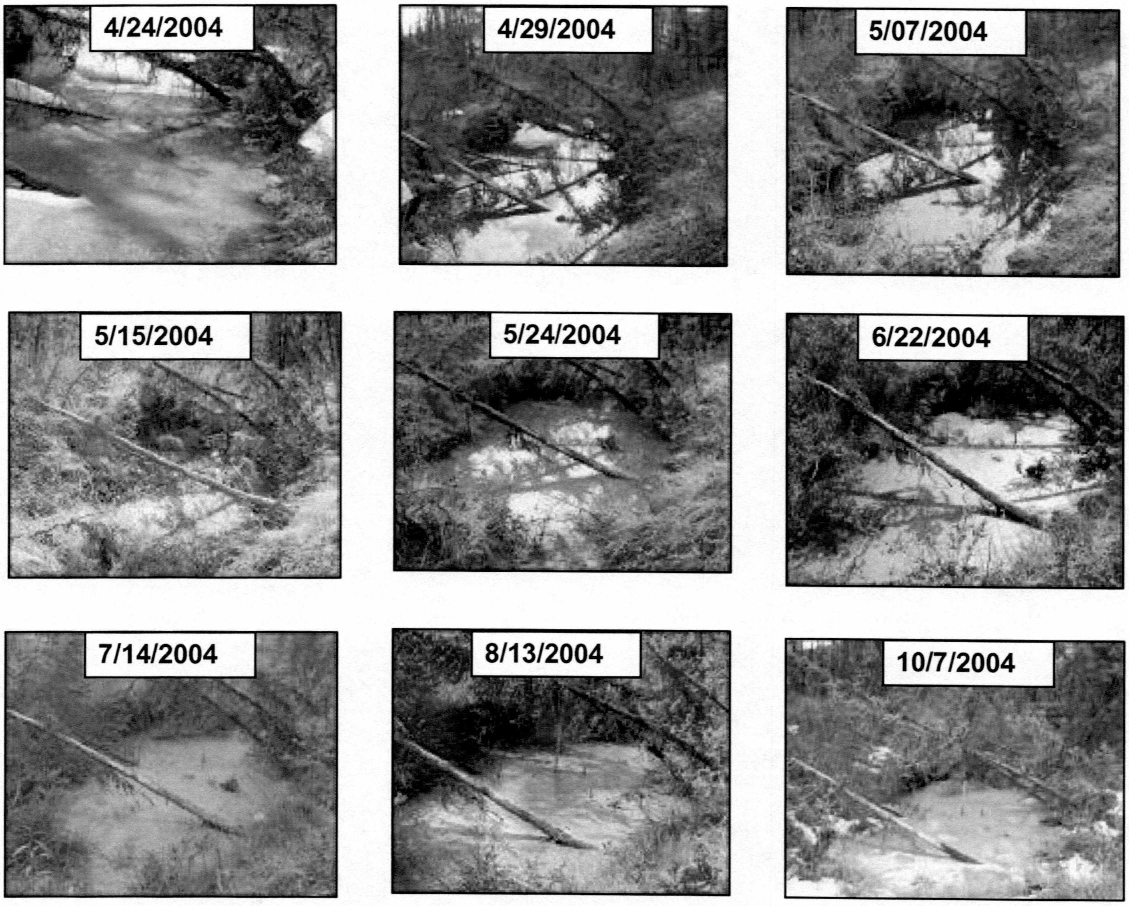


Figure 24. Time lapse sequence of thermokarst evolution of the downstream study site from 4/24/2004 to 10/17/2004.

The main difference in the style of evolution at the two study sites was that a channel was formed at the upstream site while high sediment flux was deposited in the downstream site depression. Fluvio-thermal erosion led to bank erosion and channel formation at the upstream site while groundwater flow in the sub-strata caused the soil matrix erosion at the downstream site. The effects seen in 2004 are summarized in Table 2.

Table 2. Summary of the 2004 thermokarst evolution at the two study sites.

Upstream site	**Downstream Site**
Channel formation was observed	Sediment bed infilling was observed
Bank erosion was very significant	High quantity of sediment was deposited
Fluvio-thermal erosion was the main factor	Groundwater flow was the controlling factor

4.9.2 Thermokarst evolution in 2005

In 2005, a higher erosional rate was noticed at the upstream site while thermokarst evolution at the downstream site was limited to shoreline erosion at the beginning of the field season. However, on the last field visit conducted on 10/13/2005 formation of secondary thermokarst features at the downstream site was observed. On the basis of this physical evidence it can be hypothesized that terrain modification will be much higher in the summer of 2006 at the downstream site. Deposition and re-sedimentation was evident at the upstream site. A mini channel in the upstream channel evolved when the deposited sediment was transported along the thalweg of the channel as a consequence of flowing water. The higher fluid velocity after a minor precipitation event initiated the process. Figure 25 shows the sequence of formation and development of the mini channel at the upstream site. The mini channel was first observed on 9/17/2005 after a small rain event. The channel evolved laterally as seen in the 9/27/2005 photograph. The mini channel configuration was preserved at the end of the summer as seen in the 10/13/2005 photograph.

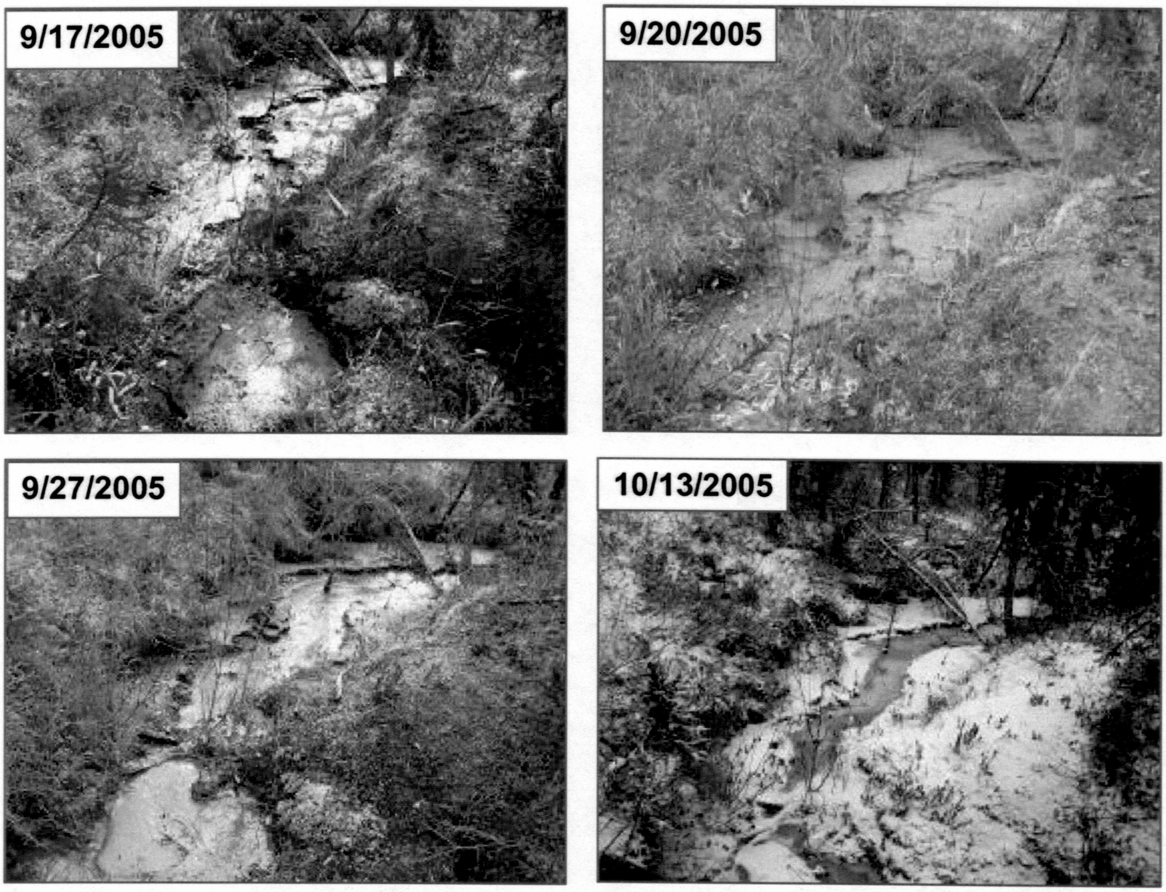


Figure 25. Mini channel formation and development observed at the upstream study site in 2005.

The changes in the channel characteristics at the upstream site that transpired during 2005 are presented in Figure 26. The first photograph taken on 4/29/2005 shows the muddy water. A significant amount of sediment was deposited in the upstream channel over the summer. The second photograph shows the mini channel developed at an advanced stage, on 9/17/2005. In addition to the mini channel formation, the upstream site also experienced bank erosion and ground subsidence.

Figure 26. 2005 thermokarst evolution at the upstream site.

4.10 Topographical surveying results

Topographical surveys performed to monitor the change in the site terrain provided interesting results. Figure 27 shows 3-D plots of the study area. Figure 27(a) indicates the terrain configuration after breakup (survey conducted on 5/24/2004). Figure 27(b) shows the topography in the same area at the end of summer (survey conducted on 10/5/2005). The upstream point moved about 2.5 m in 2004. Lateral movement at the downstream site in 2004 was about 0.5 m on both banks.

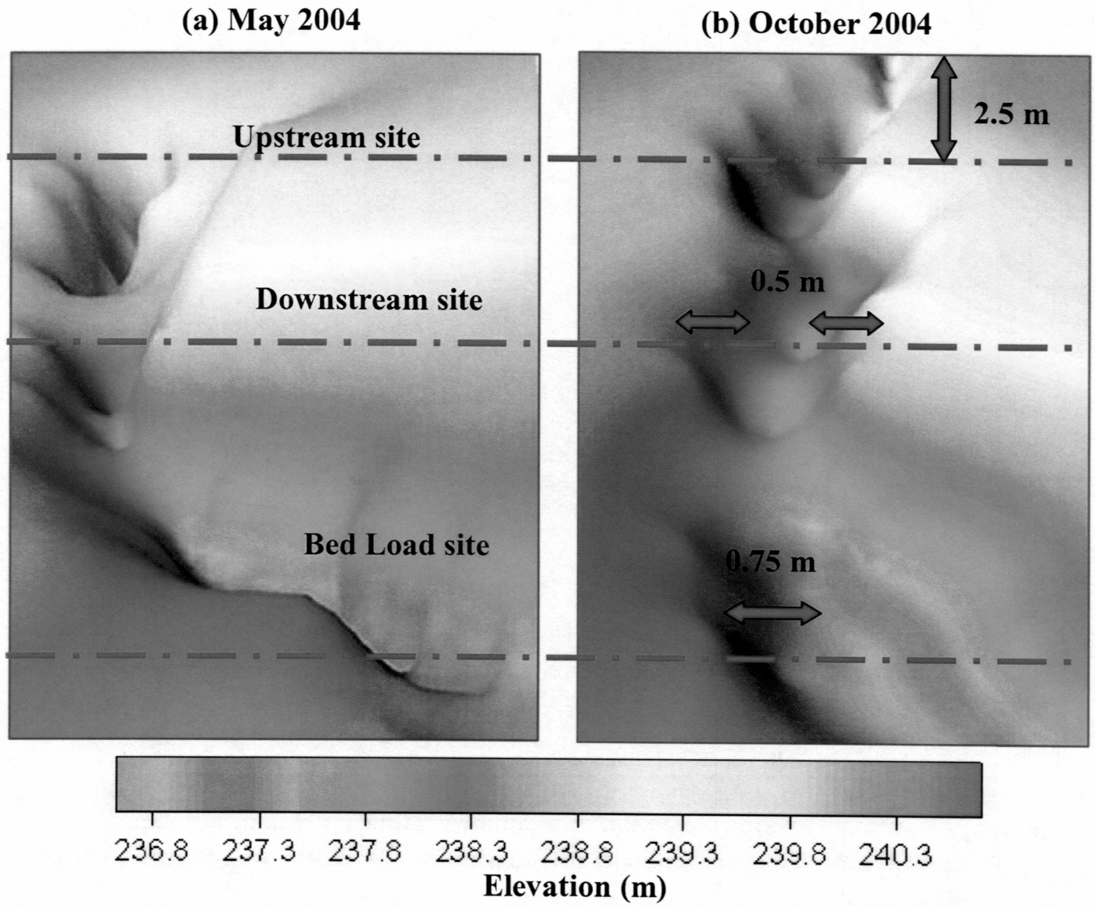


Figure 27. Representative 3-D plots of the surveys showing the lateral and upward erosion. (a) survey conducted on 5/24/2004; (b) survey performed on 10/5/2004. Flow direction in both plots is from top to bottom. Reference coordinate in the color scale is 240 m, an arbitrary datum.

Figure 28 is a plot of the survey conducted on 10/13/2005 at the conclusion of the two year research time frame. The three study sites are indicated in the plot along with the region where sediment infilling was observed. A closer examination of the plot, along with field measurements taken on the day of the survey, show that the upstream site has traversed back almost 7 meters from its original position from the time of the 5/24/2004 survey. In the intermediate reach between the upstream site and the downstream site the sediment infilling caused by cryogenic piping can be visualized from the uniform color gradient. At the bed load site, as seen in previous surveys, the erosion was more prevalent on the right bank while the left bank was relatively stable.

The topographical surveys served as a very useful tool to monitor the growth of the thermokarst from the beginning of the study in May 2004 till the end of the research in October 2005. These surveys can also be used as references for any future surveys that may be performed at the site.

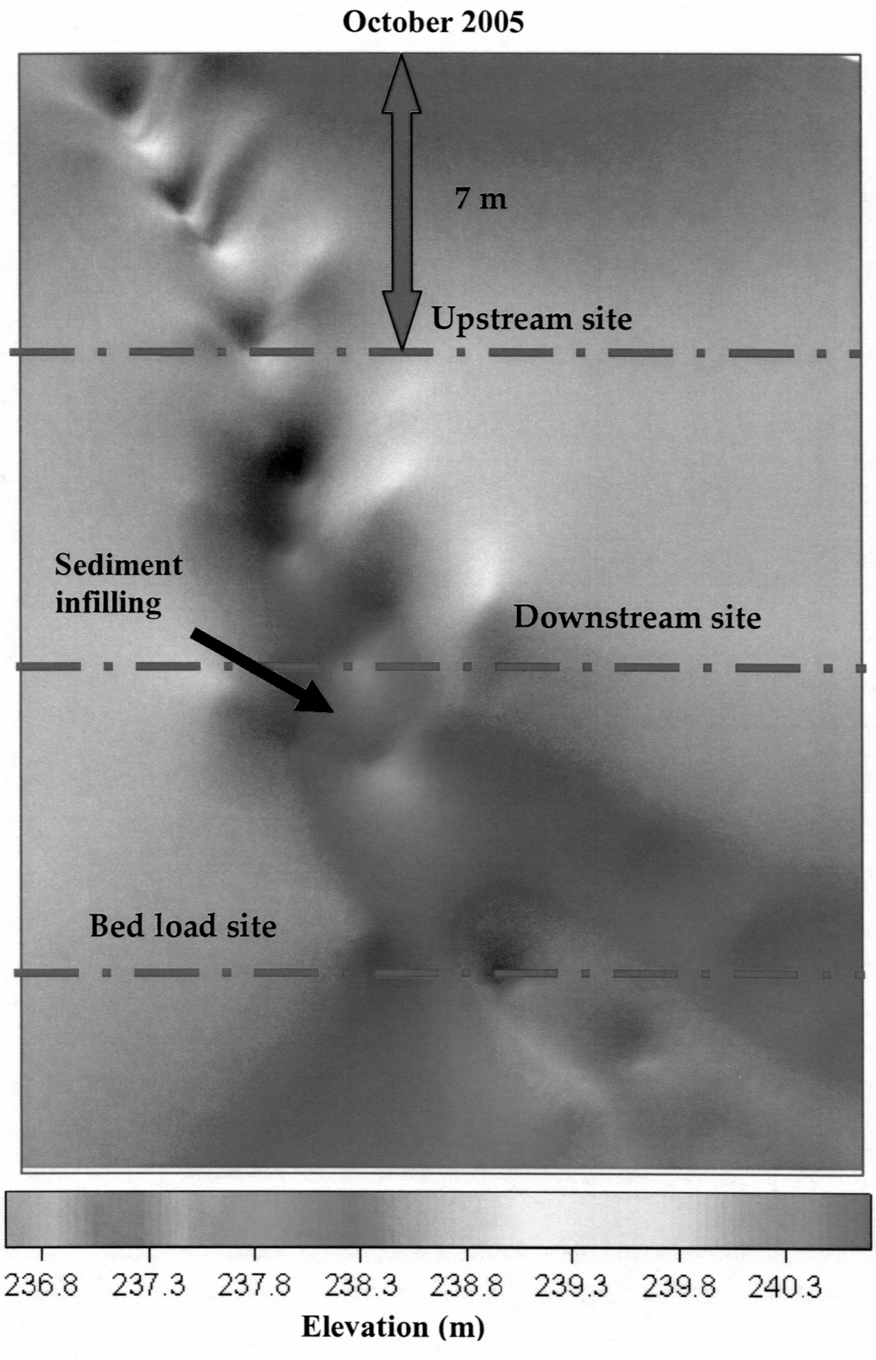


Figure 28. Representative 3-D plot of the survey conducted on 10/13/2005. Flow direction is from top to bottom. Reference coordinate in the color scale is 240 m, an arbitrary datum. Uniform gradient between upstream site and downstream site shows sediment infilling in the reach due to cryogenic piping.

Chapter 5

Conclusions and Future Work

The genesis and evolution of thermokarsts and thermokarst lakes is still one of the least understood cryogenic processes (Black, 1969). Thermokarst evolution and associated erosion, as well as sediment transport, progressed at an alarming pace throughout the CPCRW study site. The rate of growth of the thermokarst was in the range of 3.5 m/year, which can be considered to be a significant value given the stable nature of the site prior to its initiation in 2003. A slight increase in the surface temperatures will further accentuate the permafrost degradation and secondary geomorphologic structures may develop in the contiguous areas. Ground disturbance in the form of gullies and additional thermokarst have already been observed. It has made the whole area very mobile and susceptible to permafrost degradation.

This chapter is a summary of the results and observation of the two year study. It provides conclusive answers to the role of sediment transport in the evolution of the thermokarst while bringing to light very interesting and unique phenomena observed during the field studies. Due to time and resource constraints it was not possible to examine all possible research avenues. Some plausible research paths are outlined in the future work section, with optimism that these will be studied in the coming years, to yield a complete picture of thermokarst evolution.

5.1 Conclusions

The thermokarst site at CPCRW has markedly evolved in the past two summers. The main changes are related to lateral and upstream bank erosion. Active sedimentation processes in the downstream location allowed a significant volume reduction in the existing pond. Very high sediment concentration values, averaging 40 mg/g, were observed in grab samples collected during a dry-warm 2004 summer and a wet-warm 2005 summer. In 2005, cryogenic piping was a major contributor to mass sediment flows. Processes like fluvio-thermal erosion, interflow and cryogenic piping were the driving factors for the change in the site morphology.

Granulometric distribution of dried sediment samples analyzed in 2004 displayed a good correlation between discharge and sediment size, i.e., higher discharge caused huge sediment outwash and bigger sediment particles. This observation was not true during initial breakup because there was no sediment available to be transported. The opposite was observed during periods of low flow. High suspended sediment loads indicated that erosion in the area was an active and ongoing process. Sediment concentration and sediment sizes during the early breakup indicated that in spite of high water discharge, practically no sediment was in suspension. It may be an indication that no sediment was available to be moved during snowmelt, i.e., all sediment was frozen.

Climate warming in interior Alaska may lead to additional thermokarsts developing in CPCRW. Higher ground temperatures and a shift in the surface energy balance may accelerate the process (Burn and Smith, 1990; Burn and Smith, 1988). The thermokarst currently being studied is not likely to develop into a thermokarst lake due to the absence of flat topography (Kääb and Haeberli, 2001). If there are more warm summers such as 2004, and sufficient ground ice present in the vicinity, very rapid thermokarst development may lead to more slumping and undercutting of the banks. The active nature of the thermokarst can expand the impact into previously undisturbed parts of the study site (Lawson, 1982). Already a secondary channel near the downstream site has started developing quite distinctly.

5.2 Future work

Since groundwater flow in the study site was found to be an important part of the accelerated thermokarst growth, future work should look more closely at the subsurface flow network. A thorough and extensive subsurface mapping of the area using ground penetrating radar and DC resistivity studies may provide additional clues to the groundwater flow regime and the associated cryogenic processes.

Yearly topographical surveys would be useful to monitor any future thermokarst growth. Volume estimation and variation using modeling tools like ArcGIS® is another avenue that can be explored to observe the manner in which ice rich soil is eroded and sediment is transported and deposited.

Core sampling of the sediment deposited in the preexistent depressions, if conducted in the dry months, can be used to identify the type of soil gradation in the downstream preexistent depression.

Information gained from these suggestions would definitely help to better understand the overarching link between permafrost degradation and the changing climate.

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Appendix A

2004 Field Data

Table A1. 2004 Thermokarst discharge values measured at upstream and downstream sites.

Date	$Q_{U.S.}$ (l/s)	$Q_{D.S.}$ (l/s)
4/24/2004	1.11	0.98
4/29/2004	0.77	0.81
5/06/2004	0.25	0.07
5/07/2004	1.78	2.05
5/08/2004	0.56	0.46
5/09/2004	0.27	0.11
5/10/2004	0.21	0.02
5/15/2004	0.11	0.00
5/19/2004	0.10	0.00
5/24/2004	0.61	1.07
5/25/2004	0.07	0.43
5/26/2004	0.02	0.31
5/29/2004	0.00	0.11
5/31/2004	N/A	N/A
6/01/2004	N/A	N/A
6/02/2004	0.00	0.11
6/03/2004	0.02	0.19
6/07/2004	0.00	0.07
6/09/2004	0.00	0.04
6/14/2004	N/A	N/A
8/02/2004	N/A	N/A
8/03/2004	0.14	0.11

$Q_{U.S.}$ = Upstream site discharge (l/s); $Q_{D.S.}$ = Downstream site discharge (l/s);
N/A = Data Not Available

Table A2. 2004 Suspended sediment concentration values obtained from *in situ* samples collected at the upstream and downstream sites.

Date	$C_{U.S.}$ (mg/g)	$C_{D.S.}$ (mg/g)
4/24/2004	0.11	0.00
4/29/2004	0.51	0.49
5/06/2004	0.11	0.16
5/07/2004	0.13	0.37
5/08/2004	0.12	0.16
5/09/2004	0.12	0.20
5/10/2004	0.14	0.17
5/15/2004	0.06	0.00
5/19/2004	N/A	0.00
5/24/2004	0.45	40.92
5/25/2004	0.12	21.40
5/26/2004	0.10	11.30
5/29/2004	N/A	3.26
5/31/2004	N/A	5.94
6/01/2004	N/A	11.90
6/02/2004	10.10	14.80
6/03/2004	13.20	24.10
6/07/2004	N/A	25.40
6/09/2004	25.60	28.20
6/14/2004	N/A	10.03
8/02/2004	22.70	15.80
8/03/2004	20.60	12.60

$C_{U.S.}$ = Upstream site suspended sediment concentration (mg/g);
$C_{D.S.}$ = Downstream site suspended sediment concentration (mg/g);
N/A = Data Not Available

Table A3. 2004 Suspended sediment concentration obtained from autosampler samples.

Date	C (mg/g)		Date	C (mg/g)
5/27/2004	19.70		8/03/2004	20.42
5/28/2004	36.60		8/04/2004	15.40
5/29/2004	10.50		8/05/2004	5.81
5/30/2004	24.10		8/06/2004	2.20
5/31/2004	11.30		8/07/2004	2.53
6/01/2004	16.90		8/08/2004	2.34
6/02/2004	26.60		8/09/2004	2.01
6/03/2004	17.40		8/10/2004	1.56
6/04/2004	24.30		8/11/2004	1.54
6/05/2004	44.00		8/12/2004	1.36
6/06/2004	44.70		8/13/2004	1.20
6/07/2004	22.40		8/14/2004	1.09
6/08/2004	29.30		8/15/2004	0.93
6/09/2004	75.90		8/16/2004	0.79
6/10/2004	22.70		8/17/2004	0.83
6/11/2004	20.90		8/18/2004	0.81
6/12/2004	19.20		8/19/2004	0.87
6/13/2004	24.80		8/20/2004	1.11
6/14/2004	24.80		8/21/2004	0.98
6/15/2004	2.32		8/22/2004	1.36
6/16/2004	1.37		8/23/2004	1.48
6/17/2004	1.08		9/22/2004	1.14
6/23/2004	10.80		9/23/2004	0.79
7/27/2004	0.59		9/24/2004	0.88
7/28/2004	0.79		9/25/2004	0.74
7/29/2004	2.26		9/26/2004	0.49
7/30/2004	0.49		9/27/2004	0.35
7/31/2004	0.45		9/28/2004	1.59
8/01/2004	12.20		9/29/2004	0.29
8/02/2004	15.40		9/30/2004	1.93

C = Suspended sediment concentration (mg/g)

Table A4. 2004 Precipitation values recorded at the NADP rain gauge site.

Date	P (cm)	Date	P (cm)
4/21/2004	0.00	6/08/2004	0.00
4/22/2004	0.00	6/09/2004	0.05
4/23/2004	0.00	6/10/2004	0.05
4/24/2004	0.00	6/11/2004	0.38
4/25/2004	0.00	6/12/2004	0.00
4/26/2004	0.00	6/13/2004	0.13
4/27/2004	0.03	6/14/2004	0.00
4/28/2004	0.18	6/15/2004	0.00
4/29/2004	0.00	6/16/2004	0.00
4/30/2004	0.00	6/17/2004	0.00
5/01/2004	0.00	6/23/2004	0.00
5/02/2004	0.00	7/27/2004	0.00
5/03/2004	0.00	7/28/2004	0.00
5/04/2004	0.00	7/29/2004	1.27
5/05/2004	0.00	7/30/2004	0.51
5/06/2004	1.32	7/31/2004	0.25
5/07/2004	0.30	8/01/2004	1.02
5/08/2004	0.10	8/02/2004	0.51
5/09/2004	0.10	8/03/2004	0.00
5/10/2004	0.00	8/04/2004	0.00
5/11/2004	0.13	8/05/2004	0.00
5/12/2004	0.03	8/06/2004	0.00
5/13/2004	0.00	8/07/2004	0.00
5/14/2004	0.00	8/08/2004	0.00
5/15/2004	0.00	8/09/2004	0.00
5/16/2004	0.00	8/10/2004	0.00
5/17/2004	0.00	8/11/2004	0.00
5/18/2004	0.56	8/12/2004	0.00
5/19/2004	0.00	8/13/2004	0.00
5/20/2004	0.00	8/14/2004	0.00
5/21/2004	0.08	8/15/2004	0.00
5/22/2004	0.25	8/16/2004	0.00
5/23/2004	0.18	8/17/2004	0.00
5/24/2004	1.02	8/18/2004	0.00
5/25/2004	0.08	8/19/2004	0.00
5/26/2004	0.08	8/20/2004	0.00
5/27/2004	0.05	8/21/2004	0.00
5/28/2004	0.10	8/22/2004	0.00
5/29/2004	1.19	8/23/2004	0.00
5/30/2004	0.00	9/22/2004	0.00
5/31/2004	0.08	9/23/2004	0.38
6/01/2004	0.00	9/24/2004	0.00
6/02/2004	0.51	9/25/2004	0.00
6/03/2004	0.20	9/26/2004	0.15
6/04/2004	0.00	9/27/2004	0.15
6/05/2004	0.00	9/28/2004	0.43
6/06/2004	0.00	9/29/2004	0.00
6/07/2004	0.08	9/30/2004	1.35

P = Precipitation (cm)
6/24/2004 – 7/26/2004 No Data Available

Appendix B

2005 Field Data

Table B1. 2005 Thermokarst discharge values measured at upstream and downstream sites.

Date	$Q_{U.S.}$ (l/s)	$Q_{D.S.}$ (l/s)
4/27/2005	2.25	5.14
4/28/2005	4.66	4.31
4/29/2005	3.17	2.70
4/30/2005	0.83	2.34
5/01/2005	1.40	1.54
5/02/2005	0.97	0.99

$Q_{U.S.}$ = Upstream site discharge (l/s); $Q_{D.S.}$ = Downstream site discharge (l/s);

Table B2. 2005 Suspended sediment concentration values obtained from *in situ* samples collected at the upstream and downstream sites.

Date	$C_{U.S.}$ (mg/g)	$C_{D.S.}$ (mg/g)
4/27/2005	0.21	0.15
4/28/2005	1.53	0.97
4/29/2005	1.49	0.58
4/30/2005	13.44	2.31
5/01/2005	5.74	2.19
5/02/2005	3.59	2.38
6/06/2005	22.58	15.73
6/20/2005	41.32	43.81
6/21/2005	44.23	44.82
7/05/2005	44.41	44.19
7/17/2005	8.42	13.21

$C_{U.S.}$ = Upstream site suspended sediment concentration (mg/g);
$C_{D.S.}$ = Downstream site suspended sediment concentration (mg/g);

Table B3. 2005 Suspended sediment concentration obtained from autosampler samples.

Date	C (mg/g)
7/05/2005	28.65
7/17/2005	5.88
7/18/2005	15.49
7/19/2005	19.85
7/20/2005	16.36
7/21/2005	5.76
7/22/2005	15.87
7/23/2005	9.86
7/24/2005	2.39
8/02/2005	2.05
8/08/2005	5.81
8/17/2005	0.26
8/22/2005	2.51
8/28/2005	3.52
9/05/2005	0.93
9/15/2005	0.28
9/26/2005	0.83
9/27/2005	0.32

C = Suspended sediment concentration (mg/g)

Table B4. 2005 Precipitation values recorded at the NADP rain gauge site.

Date	P (cm)	Date	P (cm)	Date	P (cm)	Date	P (cm)
4/20/2005	0.00	5/31/2005	0.13	7/11/2005	0.13	8/21/2005	0.00
4/21/2005	0.00	6/01/2005	0.00	7/12/2005	0.08	8/22/2005	0.00
4/22/2005	0.00	6/02/2005	0.08	7/13/2005	0.13	8/23/2005	0.00
4/23/2005	0.13	6/03/2005	0.00	7/14/2005	0.00	8/24/2005	0.18
4/24/2005	0.13	6/04/2005	0.51	7/15/2005	0.00	8/25/2005	0.00
4/25/2005	0.00	6/05/2005	0.64	7/16/2005	0.00	8/26/2005	0.00
4/26/2005	0.00	6/06/2005	0.25	7/17/2005	0.00	8/27/2005	0.00
4/27/2005	0.00	6/07/2005	1.78	7/18/2005	0.00	8/28/2005	0.00
4/28/2005	0.00	6/08/2005	0.00	7/19/2005	0.00	8/29/2005	0.25
4/29/2005	0.00	6/09/2005	0.00	7/20/2005	0.00	8/30/2005	0.05
4/30/2005	0.00	6/10/2005	0.00	7/21/2005	0.00	8/31/2005	0.00
5/01/2005	0.00	6/11/2005	0.36	7/22/2005	0.00	9/01/2005	0.00
5/02/2005	0.00	6/12/2005	0.18	7/23/2005	0.00	9/02/2005	0.00
5/03/2005	0.13	6/13/2005	0.03	7/24/2005	0.00	9/03/2005	0.13
5/04/2005	0.00	6/14/2005	0.00	7/25/2005	0.00	9/04/2005	0.08
5/05/2005	0.00	6/15/2005	0.00	7/26/2005	0.00	9/05/2005	0.08
5/06/2005	0.00	6/16/2005	0.00	7/27/2005	0.00	9/06/2005	0.00
5/07/2005	0.00	6/17/2005	0.00	7/28/2005	0.00	9/07/2005	0.30
5/08/2005	0.00	6/18/2005	0.00	7/29/2005	0.00	9/08/2005	0.08
5/09/2005	0.00	6/19/2005	0.76	7/30/2005	0.00	9/09/2005	0.00
5/10/2005	0.00	6/20/2005	1.65	7/31/2005	0.00	9/10/2005	0.08
5/11/2005	0.00	6/21/2005	0.00	8/01/2005	0.00	9/11/2005	0.00
5/12/2005	0.00	6/22/2005	0.08	8/02/2005	0.00	9/12/2005	0.00
5/13/2005	0.13	6/23/2005	0.00	8/03/2005	0.00	9/13/2005	0.23
5/14/2005	0.00	6/24/2005	0.05	8/04/2005	0.00	9/14/2005	0.00
5/15/2005	0.13	6/25/2005	0.33	8/05/2005	0.13	9/15/2005	0.00
5/16/2005	0.05	6/26/2005	0.05	8/06/2005	0.00	9/16/2005	0.00
5/17/2005	1.40	6/27/2005	0.00	8/07/2005	0.00	9/17/2005	0.00
5/18/2005	0.64	6/28/2005	0.00	8/08/2005	0.00	9/18/2005	0.10
5/19/2005	0.00	6/29/2005	0.00	8/09/2005	0.00	9/19/2005	0.00
5/20/2005	0.00	6/30/2005	0.00	8/10/2005	0.00	9/20/2005	0.10
5/21/2005	0.00	7/01/2005	0.89	8/11/2005	0.00	9/21/2005	0.00
5/22/2005	0.00	7/02/2005	0.76	8/12/2005	0.00	9/22/2005	0.00
5/23/2005	0.00	7/03/2005	0.00	8/13/2005	0.00	9/23/2005	0.00
5/24/2005	0.00	7/04/2005	1.02	8/14/2005	0.00	9/24/2005	0.00
5/25/2005	0.00	7/05/2005	0.08	8/15/2005	0.00	9/25/2005	0.00
5/26/2005	0.00	7/06/2005	0.20	8/16/2005	0.00	9/26/2005	0.00
5/27/2005	0.00	7/07/2005	0.38	8/17/2005	0.00	9/27/2005	0.00
5/28/2005	0.00	7/08/2005	1.40	8/18/2005	0.00	9/28/2005	0.00
5/29/2005	0.08	7/09/2005	0.69	8/19/2005	0.00	9/29/2005	0.00
5/30/2005	0.00	7/10/2005	0.41	8/20/2005	0.00	9/30/2005	0.00

P = Precipitation (cm)

Appendix C

2005 Temperature Profile Data

Table C1. Temperature profile data along the left bank of the disturbed site measured on 8/7/2005.

Height from channel bed (m)	Temp. (°C)
0.00	4.5
0.08	5.2
0.23	7.2
0.30	7.9
0.41	9.3
0.50	10.2
0.58	10.4
0.69	10.8
0.76	11.7
0.85	10.6
0.94	12.3

Table C2. Temperature profile data along the right bank of the disturbed site measured on 8/7/2005.

Height from channel bed (m)	Temp. (°C)
0.00	4.1
0.08	3.8
0.15	5.1
0.23	4.8
0.30	6.9
0.41	8.1
0.51	8.3
0.64	8.6
0.76	8.7
0.89	9.8
0.99	11.2
1.12	12.9
1.19	13.3

Table C3. Temperature profile data along the left bank of the disturbed site measured on 10/13/2005.

Height from channel bed (m)	Temp. (°C)
0.00	0.2
0.10	-0.2
0.20	-0.3
0.30	-0.4
0.41	-0.3
0.51	0.1
0.64	0.1
0.76	0.1

Table C4. Temperature profile data along the right bank of the disturbed site measured on 10/13/2005.

Height from channel bed (m)	Temp. (°C)
0.00	0.2
0.13	0.2
0.25	0.3
0.38	0.3
0.51	0.1
0.64	-0.2
0.76	-0.6
0.89	-1.6
1.02	-2.1

Table C5. Temperature profile data along the left bank of the undisturbed site measured on 8/7/2005.

Height from channel bed (m)	Temp. (°C)
0.00	5.7
0.08	6.3
0.15	7.2
0.23	7.3
0.30	7.4
0.38	7.4
0.43	7.4

Table C6. Temperature profile data along the right bank of the undisturbed site measured on 8/7/2005.

Height from channel bed (m)	Temp. (°C)
0.00	6.1
0.08	5.9
0.15	5.9
0.23	6.3
0.30	6.3
0.38	6.2
0.46	6.2

Table C7. Temperature profile data along the left bank of the undisturbed site measured on 10/13/2005.

Height from channel bed (m)	Temp. (°C)
0.00	0.1
0.08	0.1
0.15	0.1
0.23	0.2
0.30	-0.2
0.38	0.7
0.46	-1.1

Table C8. Temperature profile data along the right bank of the undisturbed site measured on 10/13/2005.

Height from channel bed (m)	Temp. (°C)
0.00	0.2
0.08	0.1
0.15	0.1
0.23	0.1
0.30	0.2
0.38	-0.5
0.46	-1.4